GLAUCONY IN OCEAN-MARGIN SEQUENCE STRATIGRAPHY (OLIGOCENE–PLIOCENE, OFFSHORE NEW JERSEY, U.S.A.; ODP LEG 174A)

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ABSTRACT: **Glaucony occurs in abundance in clinoform-top and clinoform-toe positions within Atlantic-margin depositional sequences (offshore New Jersey, U.S.A.; Oligocene to Pliocene). Thin section and backscatter scanning electron microscope (BSEM) analyses indicate that grains of glaucony commonly formed *in situ* within burrows in deep-water (600–1000 m), clinoform-toe settings; fragmentation of glaucony grains in the matrix is most likely to have occurred through animal disturbance (e.g., ingestion and displacement by burrowers). Deep-water glaucony occurrences in the distal clinoform-toe positions show a pattern of association with quartz-sand abundance: in the most distal settings quartz sand is a minor component and its importance increases with proximity to the clinoform fronts. We hypothesize that these glauconitic sands, which commonly have erosional bases, formed by sediment starvation during relative sea-level rise and highstand, when the sandy clinoform fronts (deposited during sea-level lowstand) were abandoned. During particular times of regional sediment starvation over Oligocene to Middle Miocene time, biologically mediated erosion and transport were thus dominant processes in distal clinoform-toe settings, and *in situ* glaucony grains were mixed with quartz sand grains derived by degradation of the clinoform front. From Middle Miocene time onwards, development of submarine canyons may have restricted redistribution of quartz sand to discrete conduits. Sedimentary fabrics exhibited by shallow-water ($<$ 100 m) glaucony in clinoform-top settings indicate reworking through localized biological or physical means. One extremely glauconite-rich bed in the clinoform-top setting, of Pliocene age, contains the most mature glauconite, in whole grains and fragments of pellets, constituting up to 75% of the sediment. This remarkable bed likely took several million years to accumulate, a time characterized by little terrestrial sediment input. It may represent a significant horizon of at least regional extent corresponding to an extended time of overall sea-level rise during the Pliocene.**

INTRODUCTION

The occurrence of abundant glaucony at particular horizons in stratigraphic sequences is usually interpreted to be the result of slow accumulation due to sediment starvation, typically in water depths ranging from 50 to 500 m (Odin and Fullagar 1988; Amorosi 1997). Thus, in sequence stratigraphic analysis glaucony-rich beds can serve as convenient indicators of either transgressive or maximum flooding surfaces (e.g., Loutit et al. 1988, Baum and Vail 1988; Galloway 1989). In detail, however, rather diverse patterns of glaucony abundance and maturity through shallow-water shelf sequences have been documented recently (e.g., Huggett and Gale 1997; Amorosi 1997; Amorosi and Centineo 1997; Kitamura 1998; Stonecipher 1999). Moreover, when deeper-water settings have been considered, the sequence stratigraphic significance of glaucony accumulation appears even more complex, with different levels through a stratigraphic section inferred to represent all conceivable states of relative sea-level change (McCracken et al. 1996; Miller et al. 1998).

In the present study we take a petrographic approach to documentation and interpretation of the occurrence of glaucony within well-defined Cenozoic clinoform sequences typical of the Atlantic margin, offshore New Jersey, U.S.A. (Austin et al. 1998; Metzger et al. 2000). Our data come from the recently completed ODP Leg 174A and comprise distinct shallow-water and deep-water sample sets (Fig. 1). The shallow-water samples are from a clinoform-top position (Site 1072, Fig. 1) and, on the basis of micropaleontology, must have been deposited in water depths less than 150 m (Shipboard Scientific Party 1998a; Katz, personal communication). The deep-water samples are from a clinoform-toe setting that lay some 50–100 km oceanward of the clinoform fronts (Site 1073, Fig. 1); these must have been deposited in waters in the order of 600–1000 m deep on the basis of micropaleontology and seismic-reflection geometries (Shipboard Scientific Party 1998b; Katz, personal communication). Although these occurrences are of a range of ages, they were all deposited as part of a stable depositional regime that extended from the Early Oligocene through to the Pliocene, and which was characterized predominantly by progradation of siliciclastic sedimentary systems. We specifically exclude from our study sediments of Pleistocene age because these were deposited under a very different depositional regime.

This study complements and extends previous work by McCracken et al. (1996), who spot-sampled glaucony in clinoform-toe sediments recovered from the New Jersey margin during ODP Leg 150. (Recent work using spot samples from Leg 174A sites, reported by Harris and Whiting (2000), largely reproduces the results of McCracken et al. (1996).) In the present study we aimed to discover: (1) whether there are significant differences in the physical and chemical characteristics of shallow-water and deep-water glaucony occurrences; and (2) whether there are consistent associations of glaucony grains with siliciclastic-sediment grain size or biogenic-particle concentration. Our principal conclusion is that in the deep-water setting systematic patterns of glaucony abundance, quartz abundance, and grain size do occur, and on the basis of these observations we suggest a mode of origin for deep-water glaucony-rich beds different from that commonly applied. In this paper the term ''sand'' signifies grain size only and not grain composition.

New Jersey Margin Clinoform Sequences

The definition of depositional sequences by their seismic geometries is practically without rival for the Cenozoic of the New Jersey margin. Interpretations of these sequence geometries have been much debated (e.g., Greenlee and Moore 1988; Greenlee et al. 1988; Greenlee et al. 1992; Poulsen et al. 1998; Fulthorpe et al. 2000). One view, in which the strongly progradational packages within the succession are interpreted as having been deposited during relative sea-level highstand, is outlined in Christie-Blick et al. (1998); in this interpretation (following Greenlee et al. 1988) sea-level fall below the clinoform breakpoint results in deposition of a lowstand wedge, banked up at the foot of the clinoform front. Alternatively, recent detailed study of high-resolution seismic reflection profiles from the New Jersey margin (Fulthorpe et al. 1999, 2000; Metzger et al. 2000) supports an interpretation that many, if not all, progradational clinoform wedges represent phases of sea-level change from highstand, through falling stage, to lowstand. The principal pertinent observations are that onlapping geometries against the clinoform fronts are commonly absent (especially in Upper Miocene sequences) and that clinoform topsets are not incised deeply by river valleys, the latter fact indicating that relative sea level never fell significantly below the clinoform breakpoint. Even where onlapping ''lowstand'' wedges have been recognized on the basis of seismic geometries (as in the case of some Middle Miocene sequences) the

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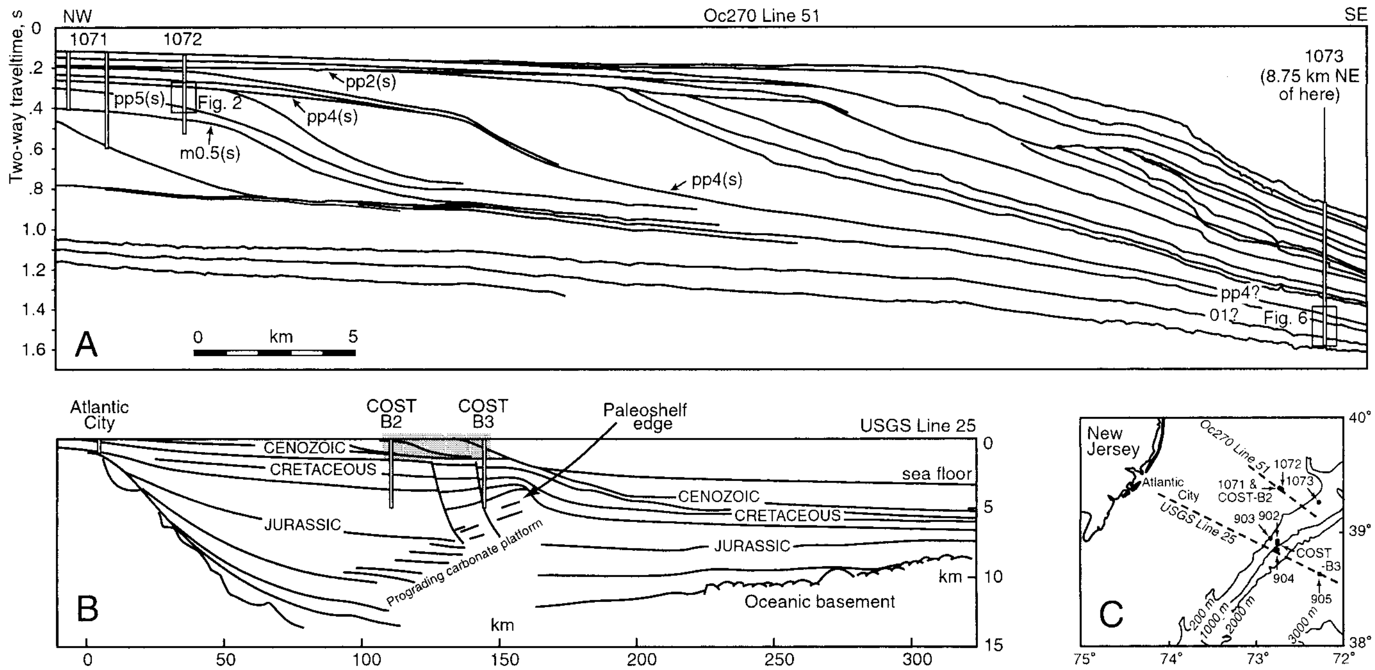

FIG. 1.—**A)** Line drawing showing positions of ODP Leg 174A sites based on seismic reflection profile Oc270 Line 51 (kindly supplied by Greg Mountain, Lamont-Doherty Earth Observatory). Boxes indicate stratigraphic intervals detailed in Figs 2 and 6. **B)** Interpreted upper crustal geology along U.S.G.S. Line 25 (from Grow et al. 1988); for further details of the Jurassic–Cretaceous section see Prather (1991); position of COST-B2 is projected. Shaded area indicates section in panel A. **C)** Location map for Leg 150, Leg 174A, and other drill sites referred to in text (see Christie-Blick et al. 1998 for detail).

depositional environments in which they were deposited are poorly characterized, and the volumes of sediment that they represent are relatively small (e.g., Greenlee et al. 1992).

Formation of Glauconite and the Glaucony Facies

The ''glaucony facies'' comprises ferric-iron-rich, glauconitic minerals with a 10–14 Å basal lattice spacing, typically occurring as green to greenish-brown pellets (Odin and Matter 1981). ''Glauconite'' is the green, potassium-rich end-member mineral of this grouping, and has a 10 Å basal lattice spacing. Glaucony forms in areas of slow sedimentation where there is a suitable substrate, a semiconfined, suboxic environment, and an abundant supply of iron. The principal substrates for glaucony are fecal pellets, tests, and phyllosilicate grains. A well-known classification system for glaucony has been devised by Odin and Matter (1981): nascent, slightly evolved, evolved, and highly evolved. Glaucony formation commences just beneath the sediment–water interface, with the formation of iron-rich smectitic clay; as glauconitization proceeds, evolved grains develop surface cracks, which may then themselves become infilled with pale green glaucony. If the infilling glaucony also undergoes maturation the pellets become uniformly highly evolved grains (e.g., Odin and Dodson 1982). With increasing maturity the potassium content increases, and the basal lattice spacing decreases. Evolved glauconite may be formed in 10^5 years, if the granules are not buried (Giresse et al. 1980). Chemical evolution (uptake of Fe and K) stops either after long exposure at the sediment–water interface or after burial to several decimeters (Odin and Matter 1981; Odin 1988). Hence glaucony is commonly associated with marine transgressions, where rapid deepening starves the shelf of sediment, and maturity of glaucony may be an indicator of the intensity of a hiatus. Potassium-rich evolved glaucony continues to mature during burial diagenesis with substitution of aluminum for iron (Ireland et al. 1983).

METHOD

Polished blocks and sections were prepared from samples spaced 0.1 to 3 m through the successions at Site 1072 (150–260 mbsf) and at Site 1073 (536–662 mbsf). The sections were point-counted to determine percentages of whole glaucony, fragmental glaucony, quartz sand, biogenic particles, and matrix (silt and clay, excluding visible glaucony particles). These data were compared with the proportion of fractured grains estimated from BSEM images. Quantitative energy-dispersive analyses of glauconitic pellets were obtained from all glaucony-rich horizons. Samples were examined in a Hitachi S2500 and a Jeol LV3500 with Oxford Instruments ISIS software. Quantitative energy-dispersive X-ray (EDS) analyses were obtained using a 2 μA beam current at 15 kV accelerating voltage.

If the backscattered electron signal is recorded, an image with mean atomic number contrast is produced. The flatter the surface, the greater the contrast, hence polished sections or blocks are used in this application. A ''gray-level'' image of the minerals is produced in which the different phases can be readily recognized, e.g., quartz appears mid-gray and pyrite white because the back-scattered electron signal intensity increases with the mean atomic number of the mineral being imaged. The image is similar to that obtained from a thin section with a light microscope, except that it has considerably better resolution (allowing good-quality images to be obtained at $\times$5000 and above).

SHALLOW-WATER GLAUCONY (SITE 1072)

Depositional Setting

The depositional and sequence stratigraphic setting of the Upper Miocene to Pliocene clinoform-top sediments at Site 1072 have been described recently (Metzger et al. 2000) using a seismic reflection and borehole database from ODP, STRATAFORM, and hydrocarbon-industry sources (cf. Austin et al. 1998). The cored interval of interest here spans the upper (and major) part of one depositional sequence and includes the lowest part of

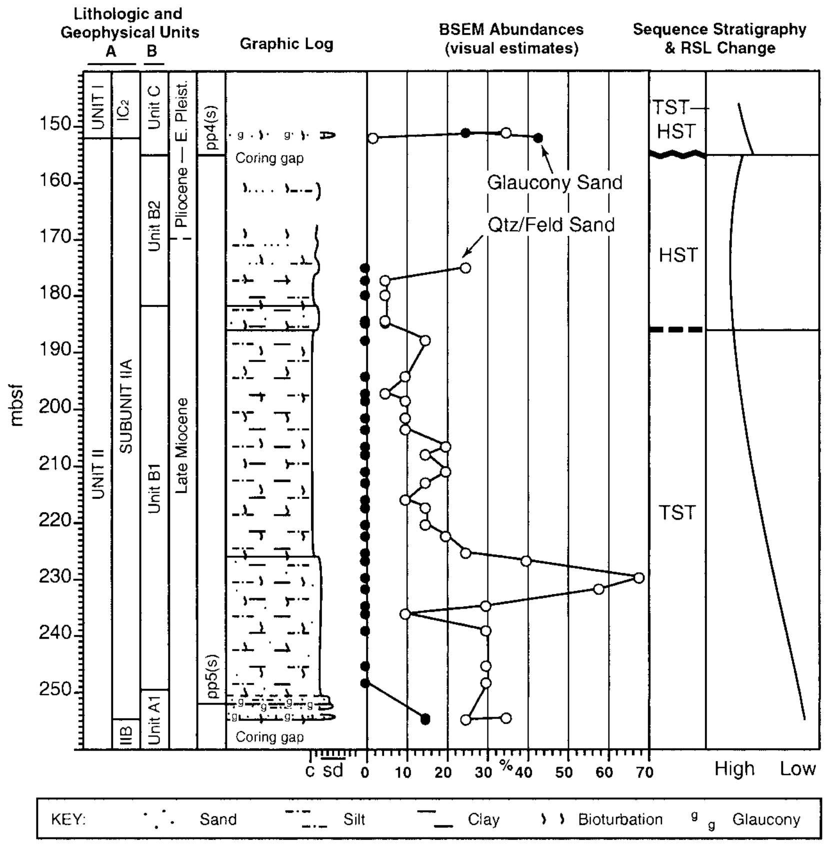

FIG. 2.—Summary of the shallow-water sedimentary succession at Site 1072 showing positions of the principal glauconitic horizons and abundances of the main sedimentary components based on visual estimate. Shipboard lithostratigraphic units (A) are from Austin et al. (1998) and lithofacies units (B) are from Metzger et al. (2000). Decreasing grain size to a maximum flooding surface at ~ 185 mbsf is indicated. TST = transgressive systems tract; HST = highstand systems tract.

another (Fig. 2). The sequence boundaries are defined in seismic reflection profiles by clear truncation of underlying clinoform reflectors. Extensive geophysical-log datasets help to define the stratigraphic succession. Below, we describe briefly the sequence stratigraphy and known age relationships where they are relevant to glaucony occurrence.

The sequence boundary labeled m0.5(s)—in accordance with an alphanumeric system applied generally to New Jersey margin sequences (Figs. 1, 2; Austin et al. 1998)—lies below the level of good core recovery at Site 1072, and is dated as Late Miocene (~ 8.6 Ma) (Shipboard Scientific Party 1998a; Katz, personal communication). The next youngest sequence boundary at the drill site is labeled pp4(s) and shows seismic reflection characteristics similar to m0.5(s). Dinoflagellate cysts recovered from ~ 10 m above the sequence boundary are dated as Late Pliocene (~ 1.8 Ma), in agreement with nannofossil evidence, although it is possible that the basal sediments of the sequence are as old as Late Miocene (< 5.4 Ma) (Shipboard Scientific Party 1998a; Katz, personal communication). The age of the immediately underlying sediments is estimated as Late Miocene (~ 5.6 Ma) (Shipboard Scientific Party 1998a; Katz, personal communication). Thus an extended period of erosion, nondeposition, or condensation is implied. A further important surface, well defined in seismic reflection profiles, lies between these sequence boundaries (labeled pp5(s) in Figs. 1 and 2). This surface is interpreted by Metzger et al. (2000) as a major flooding surface, although work in progress (Fulthorpe, personal communication) indicates that the sea-level history associated with this surface is more complex than simple flooding.

Above the surface pp5(s), at a level of poorly sorted glauconitic silty sand (see below), the succession broadly fines upwards from muddy sand to sandy mud at ~ 185 meters below sea floor (mbsf), above which level grain size again increases. This interval was assigned to lithological unit IIA by the Shipboard Scientific Party (1998a). Core recovery is very poor through the higher coarser interval of this lithologic unit, but the limited samples that were obtained, combined with geophysical-log data, indicate a predominance of sand, some of which is glauconitic. The level of minimum grain size at ~ 185 mbsf has been interpreted by Metzger et al. (2000) to represent the maximum flooding surface on the basis of core descriptions and geophysical data (see Fig. 2).

Sequence boundary pp4(s) (at ~ 155 mbsf) is overlain by an overall coarsening-upward succession assigned to Lithologic Unit I. Core recovery through the lower part of this interval was also poor, but the lowest recovered sediment here is a dark green to greenish black, poorly sorted, fine- to coarse-grained glauconite sand of 1.2 m thickness.

Petrography

Of principal concern in the present study are the thin glauconitic levels in the vicinity of surface pp5(s) (~ 255 mbsf) and above sequence boundary pp4(s) (~ 155 mbsf).

Glaucony Associated with Surface pp5(s), 254–255 mbsf.—This is a thin interval of glauconitic clay-rich sand containing 10 to 15% glaucony pellets. The pellets are 20 to 500 μm diameter, with a modal value of 200 μm. The glaucony population comprises 85–95% entire pellets, either rounded or fractured, with the rest being fragments. Ooidal coatings of immature glauconitic smectite envelope fragments as well as rounded and delicately fractured pellets (Fig. 3). The glaucony cores have a mean composition with 7.0% ($\pm$ 1.12) potassium and 3.7% ($\pm$ 0.6) aluminum. Taking into account the standard deviation, there is some overlap in aluminum values with the younger glaucony at ~ 150 mbsf but the potassium values are significantly lower (Table 1). The clay matrix is cemented by microcrystalline siderite, which constitutes approximately 10% of the rock, based on visual estimate. Rare kaolinite has replaced mica, chlorite, and glauconite. Pyrite is almost completely absent and biogenic particles occur in trace quantities. This strongly glauconitic sandy interval is overlain by

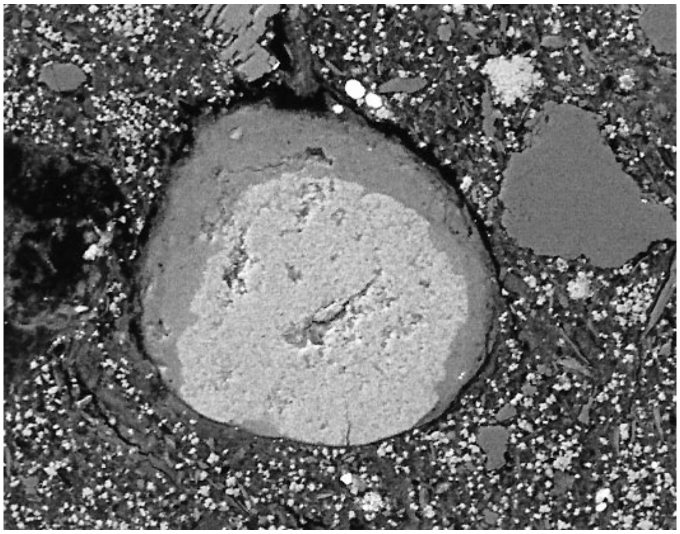

FIG. 3.—Shallow-water glaucony bed of Late Miocene age. BSEM image of section at 254.40 mbsf (interval 174A-1072A-47R-1, 20–22 cm). Ooidal coatings around mature glaucony grain with microcrystalline siderite (white) in the matrix. Horizontal field of view is 360 μm.

weakly glauconitic muddy sands with $<$ 5% glaucony pellets, of which 85 to 95% are estimated to be unfragmented. The pellets are typically smaller (50–100 μm in diameter) in these higher, finer-grained sediments.

Glaucony above Sequence Boundary pp4(s), 145–152 mbsf.—The base of this interval is a poorly sorted, clay-rich glauconitic sand with up to 75% glauconite grains, which range from 5 μm to 200 μm in diameter, though the coarser pellets constitute the greater part of the sediment (Fig. 4). The presence of abundant glaucony, forming grains and in the matrix, has resulted in the rock appearing a vivid emerald green. The chemical composition is uniformly that of mature, potassium-rich and aluminum-poor glauconite (Table 1). The angularity of the glaucony particles is well seen at high magnification (Fig. 5); angularity increases with decreasing grain size. No glaucony grains unequivocally *in situ* were observed at this level. Trace kaolinite has replaced mica, chlorite, and glauconite. Pyrite and siderite were not observed. Fragments of bivalve shells occur in trace amounts. Above the top part of this glauconitic horizon is a sandy silty clay with 5–15% very fine- to medium-grained quartz sand and 2–3% glauconite, of which 10–30% is fragmental.

TABLE 1.—*Mean values (%) for quantitative energy dispersive X-ray analyses of glaucony pellets for shallow-water and deep-water glaucony.*

Element Analyzed	Shallow water		Deep water	
	1072A Mean for 145–152 mbsf N = 28	1072A Mean for 254–255 mbsf N = 26	1073A Mean for 544–550 mbsf N = 15	1073A Mean for 604–645 mbsf N = 19
Si	48.17	48.32	49.52	50.87
Ti	0.07	0.06	0.06	0.07
Al	4.25 (± 0.42)	3.70 (± 0.60)	3.24 (± 0.75)	3.71 (± 0.55)
Fe	23.42	25.84	22.09	23.00
Mn	0.04	0.04	0.02	0.04
Ca	0.09	0.17	0.20	0.29
Mg	3.59	2.82	3.18	3.93
K	8.55 (± 0.23)	7.00 (± 1.12)	7.42 (± 0.15)	7.19 (± 0.53)
Na	0.41	0.55	0.67	0.52
Total	88.60	88.50	86.41	89.61

DEEP-WATER GLAUCONY (SITE 1073)

Depositional Setting

Depositional and sequence stratigraphic settings of the deep-water, clinoform-toe sediments are less well documented than they are for the shallow-water counterparts, even though the core recovery is considerably better (Mountain et al. 1994; Mountain et al. 1996; Austin et al. 1998). The underlying Eocene deposits here are siliceous nannofossil oozes. The oldest, Oligocene to Lower Miocene, part of the dominantly siliciclastic succession is thin, presumably condensed, and comprises alternations of variously glauconitic sands and muds. Glaucony occurs most commonly as whole sand-size grains, and less abundantly as fragments.

The interval shown in Fig. 6 has been assigned to a number of lithologic units and subunits, based on shipboard core descriptions (Austin et al. 1998). The interval of interest here all belongs to Unit II. Above the very weakly glauconitic Eocene pelagic sediments are muddy glauconitic sands arranged in two fining-upwards cycles and assigned to Subunit IIF. This 18-m-thick succession is of Oligocene age and deposition of these sedi-

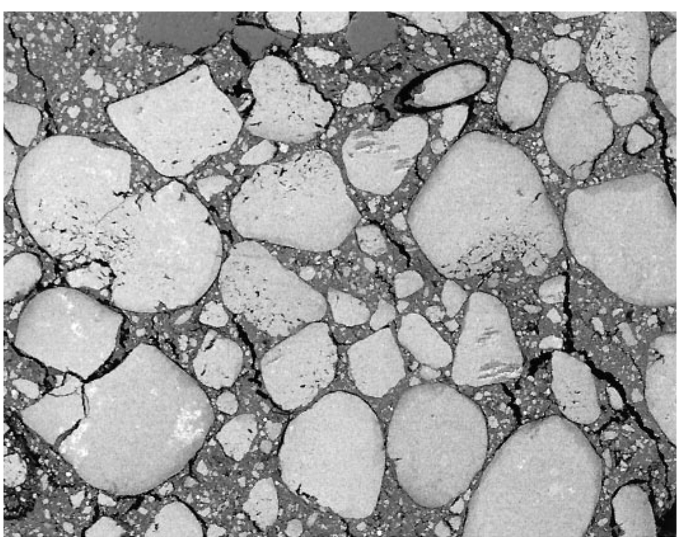

FIG. 4.—Shallow-water glaucony bed of probable Late Miocene–Pliocene age. BSEM image of sample at 151.90 mbsf (interval 174A-1072A-27R-1, 97–99 cm). See Fig. 5 for detail. Horizontal field of view is 1220 μm.

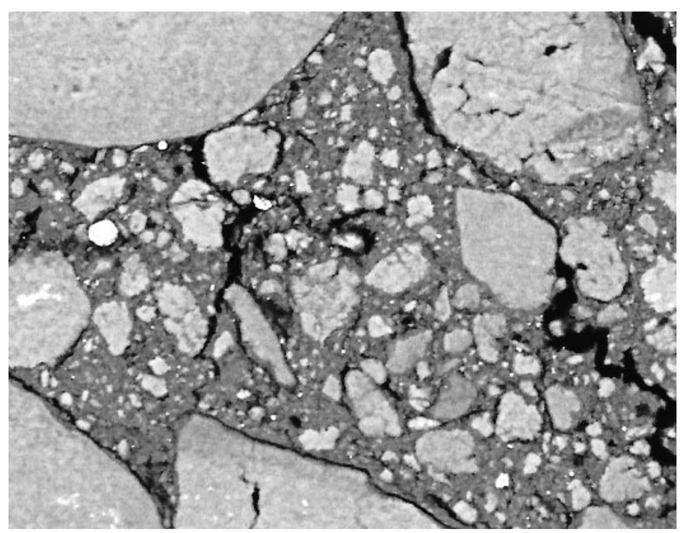

FIG. 5.—Shallow-water glaucony bed of probable Late Miocene to Pliocene age. BSEM image of sample at 151.90 mbsf (interval 174A-1072A-27R-1, 97–99 cm). Abundant angular glauconite fragments making up the matrix are clearly imaged. See also Fig. 4. Horizontal field of view is 170 μm.

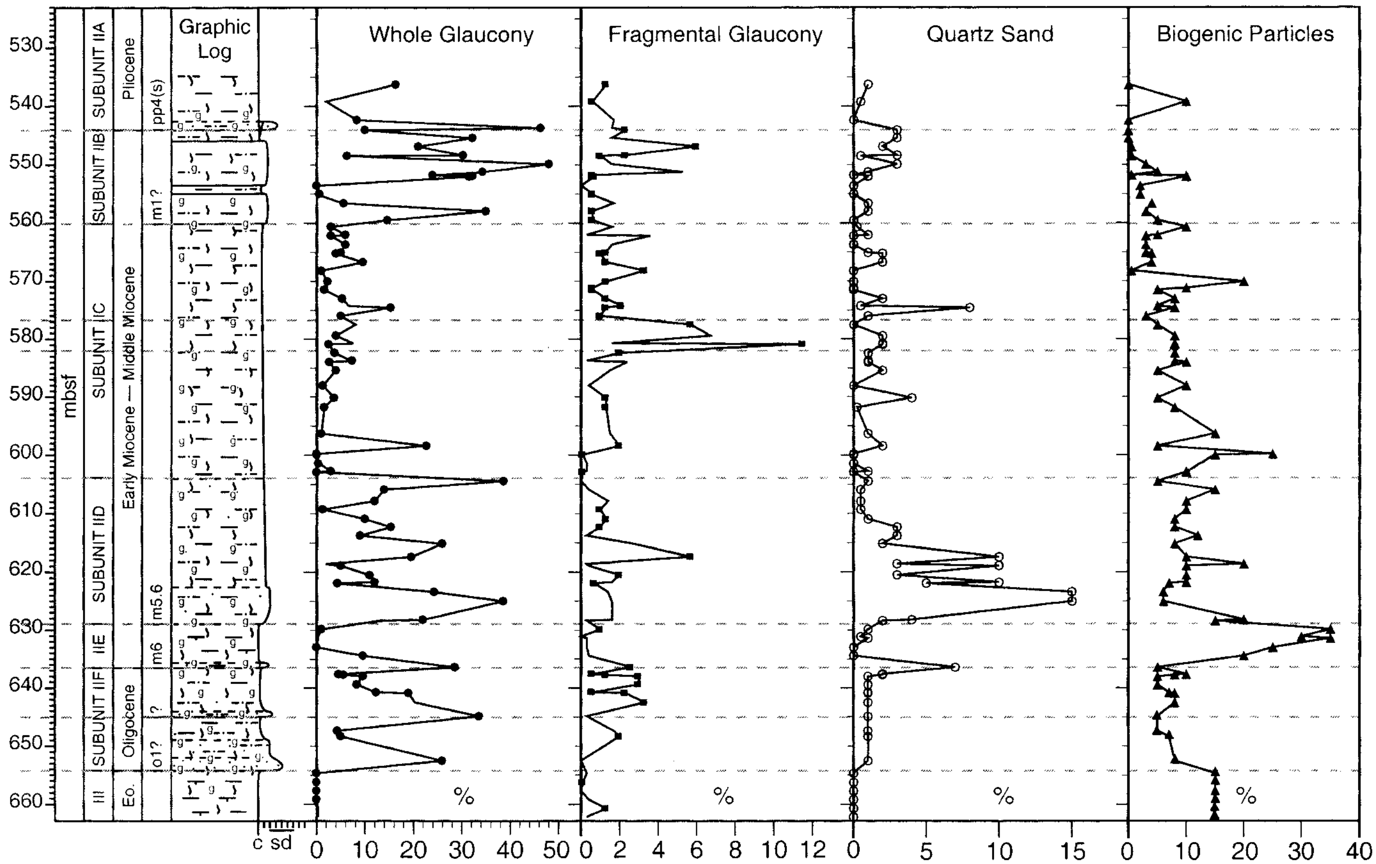

FIG. 6.—Summary of the deep-water sedimentary succession at Site 1073. Graphic log and stratigraphic units based on Shipboard Scientific Party (1998b). For key see Fig. 2. Grain abundances are based on point-counting of thin sections. Significant stratigraphic surfaces are indicated with dashed lines in gray tone. Age constraints are biostratigraphic (Shipboard Scientific Party 1998b). Subunit IIB may, at least partially, equate to the super-rich glauconite bed of Late Miocene–Pliocene age at Site 1072.

ments took place ~ 75–100 km seaward of the coeval clinoform fronts. Biostratigraphic definition of hiatuses is poor, but Sr-isotope stratigraphy (Savrda et al. 2001) indicates hiatuses or extreme condensation at ~ 653 and ~ 645 mbsf, i.e., at the bases of the glauconitic sands.

The next youngest subunit (IIE) is thin (7 m), and represents a brief return to pelagic deposition in the earliest Miocene after deposition of a thin glauconitic sand. These pelagic sediments are overlain by an expanded succession of glauconitic muds and sands, of Early–Middle Miocene age, representing the toesets of advancing siliciclastic clinoform wedges, whose clinoform fronts were only ~ 50 km distant from the drill site by the time the upper sediments were deposited. Within this package of strata, the lowest 25 m are strongly glauconitic and assigned to Subunit IID; the middle 44 m are less strongly glauconitic and assigned to Subunit IIC; and the upper 16 m, assigned to Subunit IIB, are again strongly glauconitic. Biostratigraphic definition of hiatuses within this part of the section is also poor (Shipboard Scientific Party 1998b), but Sr-isotope stratigraphy indicates hiatus or extreme condensation at the bases of or within glauconitic sandy horizons at ~ 635 mbsf and 625 mbsf (Savrda et al. 2001). The age of Subunit IIB is poorly known and may span any part or whole of the interval 13.0 to 4.5 Ma (Late Miocene to Early Pliocene).

The Lower to Middle Miocene sediments (including Subunit IIB) are abruptly overlain by thin (1 m) glauconitic sand, followed by a thick succession of weakly glauconitic muds of Pliocene to Pleistocene age. The bulk of these formed the upper continental slope at a time when clinoform geometries were no longer well developed (Shipboard Scientific Party 1998b).

Petrography

Glaucony is present throughout the cored interval at Site 1073 but is concentrated between 603 and 655 mbsf and between 539 and 560 mbsf (Fig. 6). Between the two broad intervals of abundant glaucony there is a background level of around 5% glaucony in clay-dominated, quartz-poor, and biogenic-particle-poor sediment. Glaucony fragments are most abundant in intervals where whole glaucony is scarce, but they rarely exceed 5% of the total sediment volume. Chemical composition is uniform and is similar to that of glaucony from the lower glauconitic levels at site 1072; it is less mature than the glaucony in the sediment above sequence boundary pp4 at Site 1072. Throughout the sampled interval the only other neoformed mineral is rare pyrite (1 to 2%).

In the Oligocene and Lower Miocene section, glaucony occurs in the lowest parts of three sharp-based fining-upward cycles, but above this the glaucony is unevenly distributed through both coarsening-upwards and fining-upwards successions. The two concentrations of glaucony in Oligocene Subunit IIF (sampled at 652.52 mbsf and 644.88 mbsf) both consist of 25–30% glaucony in silty clay, which is apparently otherwise indistinct from the intervening silty clay. The larger glaucony pellets in particular are clearly concentrated in burrows (Fig. 7), and glaucony commonly occurs as replacements of microfossils, as well as the more usual fecal pellets; it is commonly delicately fractured and slightly fragmented. The glaucony concentration (30%) in the earliest Miocene sediment sampled at 636 mbsf coincides with an increase in sand-size quartz in what is still predominantly silty clay. In all three of these glauconitic intervals, glaucony pellets are

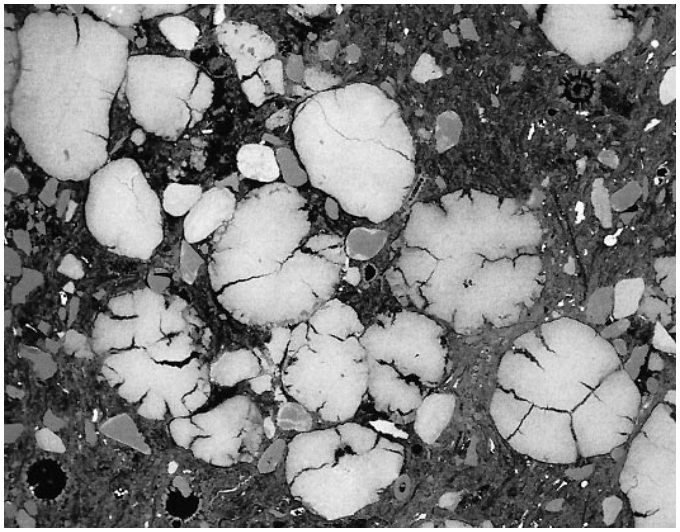

FIG. 7.—Deep-water glaucony. BSEM image of polished section at 644.88 mbsf (interval 174A-1073A-71X-1, 17–19 cm) showing high glaucony content combined with low quartz sand content. The sediment fabric is very heterogeneous with whole glaucony grains concentrated in a burrow that runs from top left to bottom right. Horizontal field of view is 1625 μm.

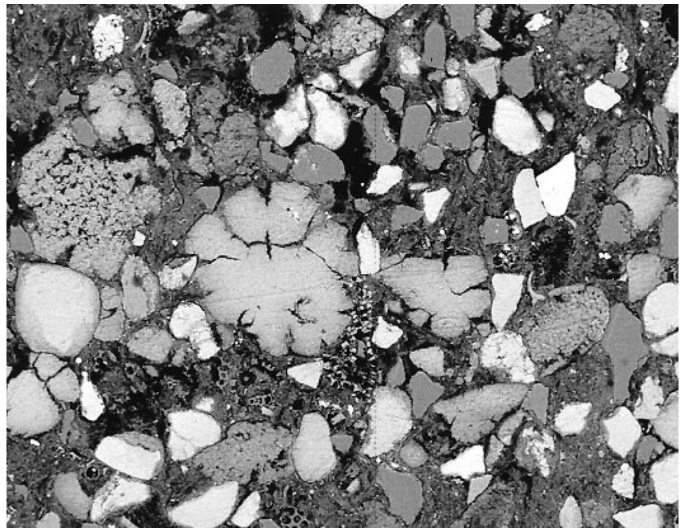

FIG. 8.—Deep-water glaucony. BSEM image of sample from 625.03 mbsf (interval 174A-1073A-68X-6, 73–75 cm) showing high glaucony content combined with high quartz sand content. Horizontal field of view is 1220 μm.

coarser (the modal diameter is 200 μm) than in the intervening glaucony-poor sediment (where the modal diameter is 60 μm).

In Subunit IID, the glaucony-poor section between 646 mbsf and 625 mbsf is an interval in which biogenic particles (mostly radiolarians and foraminifers) constitute up to 35% of the sediment. At 625 mbsf and around 615 mbsf, glaucony concentrations of 40% and 25% coincide with increased quartz sand, though the sediment is still predominantly clay (Fig. 8). Above 615 mbsf almost all glaucony concentrations occur in clay-dominated sediment with $<$ 5% sand. Where $<$ 10% glaucony is present, pellets are typically 60–70 μm, but where pellets constitute 20–50% of the sediment, size ranges up to 300 μm. The glaucony-rich beds of Subunit IIB are not associated with abundant quartz sand.

DISCUSSION

Recognition of *in situ* Versus Reworked Glaucony.—For glaucony to be a useful environmental indicator it is essential to distinguish *in situ* glaucony grains from glaucony grains that have been reworked from much older sediments, or those redistributed penecontemporaneously from their sites of origin. The criteria used for the identification of *in situ* and reworked glaucony have been discussed recently in McCracken et al. (1996), Huggett and Gale (1997), and Amorosi (1997). The principal criterion used to identify reworking in several past studies is pellet fragmentation, but this has to be applied in conjunction with interpretation of other fabric characteristics of the host sediment. In particular, it is important to consider that glaucony granules may be broken up and ''reworked'' by burrowing organisms within the bed in which they formed: such grains are essentially still *in situ* despite being fragmented. (In contrast, it is also conceivable that some granules may be reworked without being fragmented (cf. Amorosi 1997; Huggett and Gale 1997), but this is unlikely in the case of those mature grains that have well-developed rim fractures.)

In the context of Leg 174A, the glauconitic intervals are generally thinner at the shallow-water site (Site 1072) than they are at the deep-water site (Site 1073). The greater content of potassium and aluminum in the upper horizon of the Site 1072 glaucony, compared with the lower horizon at that site and all the deep-water glaucony, signifies a higher degree of chemical maturity. High chemical maturity is achieved through a long residence time close to the sediment–water interface, i.e., slower deposition. It is also noteworthy that there is no evidence to suggest re-exhumation and oxidation of previously formed glaucony in this upper bed: there is a continuum of glaucony textures from fragmental to whole, but strikingly uniform levels of maturity. Also in the upper glauconitic level at Site 1072 (around 151 mbsf), the wide range of glaucony particle size, and the decrease in angularity with increasing size, suggests that although many pellets have been broken up, they are still almost *in situ* because physical transport would have resulted in size sorting. There is, however, no unequivocal evidence for *in situ* formation of glaucony, such as unfragmented glaucony concentrations in burrows.

In the lower glauconitic horizon at Site 1072, the presence of abundant fragments, some slightly rounded, and some grains with ooidal coatings of immature glaucony (glauconitic smectite) are potentially indications of physical reworking, though opinion is divided as to whether coated grains of this kind are indicative of rolling or not (Hemingway 1974; Van Houten and Purucker 1984). Whilst ooidal coatings around grains and grain fragments are consistent with a rolling origin, it is difficult to envisage how delicately fractured pellets with ooidal coatings could have formed without becoming disaggregated.

The lower proportion of entire glaucony in the shallow-water settings compared to the deep-water settings is consistent with a greater degree of reworking and, in the case of the upper glauconitic horizon, total homogenization of the sediment by biological processing over a very long time. Age constraints around the level of sequence boundary pp4 allow as much as 3.8 Ma for this bed to form, most of this during the Pliocene (see above).

In deep-water settings glaucony is especially concentrated in burrows (e.g., Fig. 7). These glaucony pellets are largely entire grains, many deeply fractured, and it is questionable whether they could have been reworked without becoming fragmented. In the matrix between burrows a high proportion of the glaucony is fragmented, and these pellets are typically smaller than those in burrows. This indicates that more than one generation of glaucony may be present, the earliest-formed grains likely being fragmented in the guts of deposit feeders or through physical disturbance by other burrowers.

Furthermore, although benthic foraminifers are rare or absent through the Oligocene to Lower Pliocene succession at Site 1073, those few samples that have yielded specimens are dominated by diverse *in situ* assemblages characteristic of deep water (Shipboard Scientific Party 1998b). Reworking of foraminifer tests from shallow-water settings does not appear

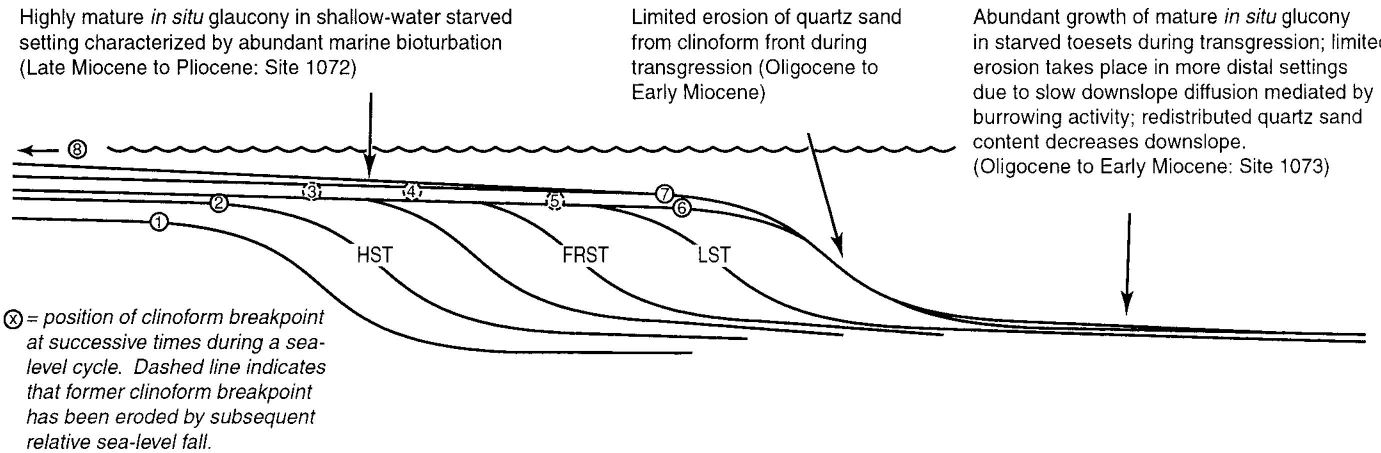

FIG. 9.—Cartoon summarizing the spatial distributions of glaucony occurrences in relation to New Jersey clinoform sequences during sea-level rise and highstand as discussed in the text. See Fig. 10 for detail of the toeset facies. Systems tracts are labeled using the criteria of Helland-Hansen and Martinsen (1996). Note that many cycles of sea-level rise and fall occurred through the Oligocene to Pleistocene.

to have been an important process during deposition of this part of the succession (in contrast to the Pleistocene succession at the same site, which is dominated by downslope transport: Shipboard Scientific Party 1998b). The *in situ* versus reworked nature of the deep-water glaucony grains is further discussed below in the context of the grain-abundance data shown in Fig. 6.

Glaucony Concentration in Relation to Sea-Level Change and Sequence Stratigraphy.—Even though the clinoform-toe sediments are located in deep water and are thin in comparison to up-dip clinoform-front equivalents, it cannot necessarily be concluded that their thinness is entirely due to starvation at the tailend of the sediment transport path. Thinning of the deep-water clinoform toesets in this region may well have resulted partly from a basement control exerted by the steep outer margin and uncompactable nature of the Late Jurassic–Early Cretaceous carbonate platforms (Fig. 1; cf. Klitgord et al. 1988; Grow et al. 1988). This ''paleoshelf edge'' must certainly have governed the stratigraphic geometries of the Pleistocene sediments once all available shelfal accommodation had been infilled on its landward side (cf. Ross et al. 1994).

However, for the New Jersey margin, clear stratigraphic patterns are shown by the deep-water clinoform-toe sediments inboard of the paleoshelf edge, and these are well displayed by the succession at Site 1073. Here, the most distal sediments comprise sharp-based glauconitic sands arranged in fining-upward cycles. Using strontium-isotope stratigraphy applied to Leg 150 sites, Miller et al. (1996) demonstrated that the sharp bases typically represent hiatuses or extreme condensation, each representing roughly 1 to 2 Ma (cf. Savrda et al. 2001).

It is an important question whether sand-size glaucony occurs in greatest abundance at the same levels as quartz sands. In Oligocene deep-water glauconitic sands recovered during Leg 150, McCracken et al. (1996) recognized that the glaucony grains were *in situ* and, because of apparent lack of sand-grade quartz, they interpreted them to be occurring within transgressive systems tracts. Alternatively, Miller et al. (1998, p. 579, 589) noted the common occurrence of quartz sand with glaucony in the clinoform-toe settings and interpreted the glauconitic sands to represent lowstand deposits commonly underlain by unconformities representing the sequence boundary. One significant problem with such an interpretation is identification of the processes that formed the basal erosion surfaces: obviously, wavebase cannot have played any role in their genesis at such depths.

The point-count data of the present study show simple patterns of quartz and glaucony abundance through the deep-water Oligocene–Lower Miocene section. The lowest two sharp-based and fining-upward cycles contain abundant and large glauconite pellets but little sand-size quartz (Figs. 6, 7). The glaucony-rich intervals do, however, contain more quartz than the intervening less glaucony-rich strata (Fig. 6). Passing upward through the Oligocene–Lower Miocene succession, the glauconitic sands contain progressively larger quantities of quartz sand and smaller glaucony pellets. Higher stratigraphic levels show a somewhat different pattern: in particular the glaucony concentration in the poorly dated interval just below the sub-Pliocene unconformity has relatively little quartz sand.

For the Oligocene and Lower Miocene aged section, it is apparent that high *in situ* glaucony abundance is coincident with raised quartz sand content in these clinoform-toe settings, and the highest glaucony/quartz ratios occur in the most distal facies. If quartz sand had been preferentially transported into the basin during sea-level lowstands, it would follow that these levels of glaucony abundance would also correspond to sea-level lowstands. However, we would expect sea-level lowstand to increase accumulation rates of siliciclastic sediment in this deep-water setting—and this is incompatible with the abundance of *in situ* glaucony and Sr-isotope evidence for hiatus or condensation. It might be argued that during lowstands most fine-grained siliciclastic sediment bypassed this area, perhaps by focusing of sediment transport within a few incised valleys and attached channelized submarine dispersal systems. Such an explanation is unlikely, however, because extensive canyon systems that could have acted as conduits for bypassing sediment are not present in the clinoform toesets of the appropriate age (Fulthorpe and Austin 1998; Fulthorpe et al. 2000). Moreover, there is the evidence to indicate that sea level never dropped significantly below the clinoform breakpoints even at lowest sea-level stand (Fulthorpe et al. 1999, 2000). Thus we suggest that quartz sand concentrated within the glauconitic sandy facies is likely to have been derived from the clinoform fronts over extended periods of time; this process would have become predominant when normal sediment supply to the clinoform fronts ceased as a result of relative sea-level rise (Figs. 9, 10). A quartz sand grain would have had to move downslope at an average rate of only 10 cm per year in order to cover a distance of 100 km in 1 Ma.

What then was the erosional process operating to form the unconformities below the glauconitic sands? Core photographs and descriptions show that much glauconitic sand is piped down into the underlying sediment in various burrows, e.g., *Thalassinoides.* (Shipboard Scientific Party 1998b; Savrda et al. 2001). Thus a considerable quantity of the underlying sediment must have been excavated by the burrow makers (see, e.g., Nowell et al. (1981) or Twitchell et al. (1985) for similar effects in modern settings). Much of this biologically disturbed material would have been transported downslope by further animal activity (e.g., Baird 1981; Hesselbo and Palmer 1992; Coe and Hesselbo 2000). If rates of transport away

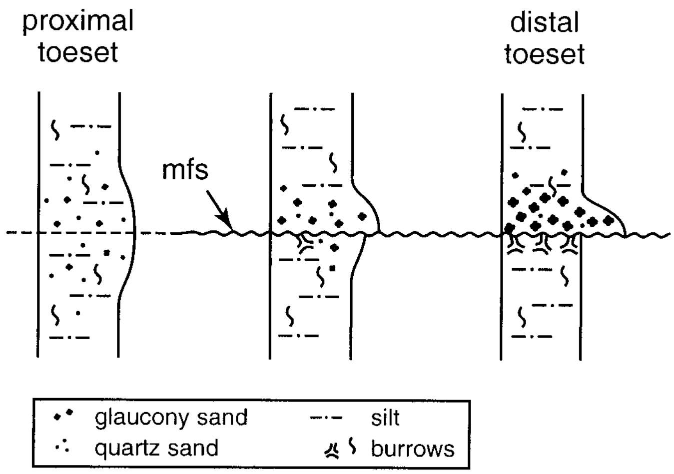

FIG. 10.—Cartoon showing hypothesized relationship between distance to clinoform front and the toeset facies associated with maximum flooding surfaces (cf. Fig. 9). The proximal toeset facies is characterized by small *in situ* glaucony grains mixed with common quartz sand, whereas the distal toeset facies is characterized by common large *in situ* glaucony grains mixed with sparse quartz sand and is floored by a well-developed bioerosional surface. mfs = maximum flooding surface.

from an area by this mechanism were greater than rates of delivery of new sediment, erosion would have been the net result. In the clinoform-toe setting of interest here, such erosion would cease only when (fine-grained) clastic supply increased sufficiently during phases of clinoform progradation.

Complications ensued in the late Middle to Late Miocene, when a number of broad, flat-bottomed ''canyons'' did form, through massive slope failure of previously deposited clinoform-toe sediments, amongst other processes. This appears to have occurred when clinoform fronts had migrated to within about 10 km of the site (Mountain et al. 1996) and slope failure was possibly induced by sediment loading and associated pore-fluid flow (Hesselbo 1996; Dugan and Flemings 2000; Fulthorpe et al. 2000 and references therein). The ''canyons'' thus formed subsequently served as traps for deposition of quartz sands that were presumably derived from the sandy clinoform front, or directly from river systems supplying the clinoform front. The evidence suggests (Mountain et al. 1996) that once formed, canyon systems were episodically relocated in the same geographical positions; lack of quartz sand in the strongly glauconitic section between 545 and 560 mbsf at Site 1073 may relate to different (more focused) sediment dispersal systems operating in these later times when canyons were well established.

Finally, we note that the Pliocene shallow-water, clinoform-top concentration of glaucony on the outer continental shelf and upper slope is compatible with indications of global early to mid-Pliocene sea-level rise, linked to mid-Pliocene Antarctic warmth (cf. Webb et al. 1984; Dowsett et al. 1994; Kennett and Hodell 1993; Wilson et al. 1998; and references therein). Stratigraphic data indicative of a similar Pliocene sea-level history have been described for other eastern U.S. Atlantic margin settings (e.g., Krantz 1991).

SUMMARY AND CONCLUSIONS

In the deep-water setting, concentration of larger (and more fragile) fractured glaucony pellets in burrows indicates likely *in situ* formation. These glaucony pellets therefore formed at 600–1000 m water depth, and they were not transported from shallow water by turbidity currents, for example, as has been suggested for many other deep-water occurrences of glaucony.

Fragments of glaucony grains form a minor component of deep-water glaucony occurrences. They occur dispersed in clay matrix between distinct burrows and were probably broken up by early burrowing activity.

Glaucony is associated with quartz sand only in the more proximal of the deep-water cycles. We suggest that the quartz sand was derived locally from the degradation of lowstand clinoform-wedges after these had been abandoned following sea-level rise. Under these conditions, sedimentation rate and grain-size characteristics were ideal for the formation of glaucony.

In the shallow-water settings, the high degree of fragmentation and the presence of ooidal glaucony around more mature pellets or pellet fragments indicate that a high proportion of the glaucony grains have been reworked or transported after growth. The balance of physical versus biological reworking remains uncertain.

The shallow-water glaucony of probable Pliocene age is chemically more mature than either the shallow-water Late Miocene glaucony or the deep-water Oligocene to Miocene glaucony. This indicates that the contained glauconite had a longer residence time in the suboxic zone; i.e., it occurs in a more condensed section. This Pliocene glauconite sand may represent a maximum flooding surface, or a distal amalgamation of such surfaces, of particular regional or even global significance.

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