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Pollen and Spores Date Origin of Rift Basins from Texas to Nova Scotia as Early Late Triassic

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Palynological studies of the nonmarine Newark Supergroup of eastern North America and of rift basins in the northern Gulf of Mexico facilitate correlation with well-dated marine sections of Europe. New information emphasizes the chronological link between the Newark basins and a Gulf of Mexico basin and their common history in the rifting of North America from Pangea. Shales from the subsurface South Georgia Basin are shown to be of late Karnian age (early Late Triassic). The known time of earliest sedimentation in the Culpeper Basin is extended from Norian (late Late Triassic) to mid-Karnian, and the date of earliest sedimentation in the Richmond and Deep River basins is moved to at least earliest Karnian, perhaps Ladinian. The subsurface Eagle Mills Formation in Texas and Arkansas has been dated palynologically as mid- to late Karnian. The oldest parts of the Newark Supergroup, and the Eagle Mills Formation, mostly began deposition in precursor rift basins that formed in Ladinian to early Karnian time. In the southern Newark basins, sedimentation apparently ceased in late Karnian but continued in the northern basins well into the Jurassic, until genesis of the Atlantic ended basin sedimentation.

THE TRIASSIC-JURASSIC FAULT-bounded basins of the eastern United States and Canada (Fig. 1) contain nonmarine clastic rocks, minor tholeiitic extrusive igneous rocks, and diabase plutons and dikes, now referred to the Newark Supergroup (*1*). The basins themselves are commonly called the Newark basins. Because these rocks contain no marine fossils, their correlation with European sections was long problematic, although abundant vertebrate and megafossil plant fossils are found at various localities throughout the basins. When it was discovered that abundant fossil spores and pollen occur not only in the coals and other relatively rare carbonaceous rocks in a few of the basins, but also in gray shales found among the prevailing red sandstones and shales of all of the Newark basins (*2*), the possibility of correlating with European sections containing both palynofloras and marine fossils was realized. The original broad-scale palynostratigraphy suggested for the major basins has held up quite well since its proposal a decade ago (*3*). More recently, because the palynomorph forms were well known from previous study of the floras in the basins just mentioned, it has also proved possible to date shales from the Cow Branch Formation of the Danville–Dan River Basin of Virginia–North Carolina as mid- to late Karnian, despite the poor state of preservation of the palynomorphs (*4*). The Fundy Basin of Nova Scotia and New Brunswick, Canada, has yielded only a few palynoflorules, largely because aeolian red beds predominate, but nevertheless palynoflorules have provided enough information to date most of the sedimentary rock of the basin as ranging from at least as old as mid-Karnian to Pliensbachian (Early Jurassic) (*5*).

As a result of recent palynological studies (*6*) considerably more information about the correlation and dating of the sedimentary rocks of these basins has become available. Newly discovered palynologically productive localities in the Culpeper Basin of Virginia and Maryland have extended the known age of the oldest rocks of this basin downward to mid-Karnian (Fig. 2). Extensive investigation of the Taylorsville, Richmond, and Deep River basins (*7*) has extended the age of their sediments to at least earliest Karnian, possibly late Ladinian (previously, none older than mid-Karnian was

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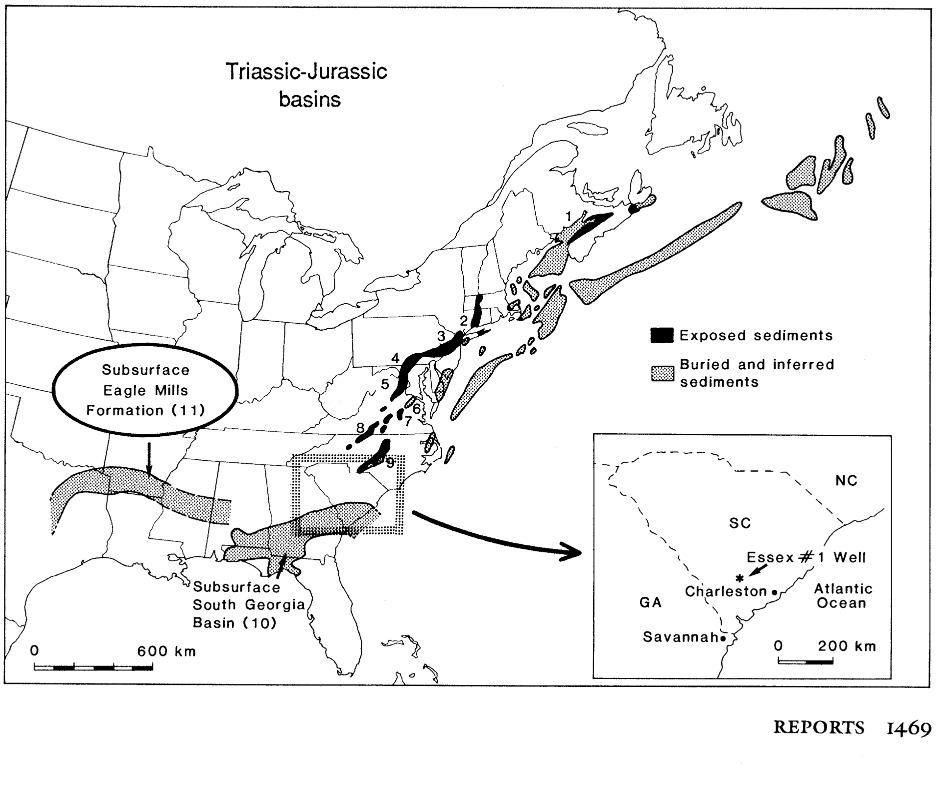
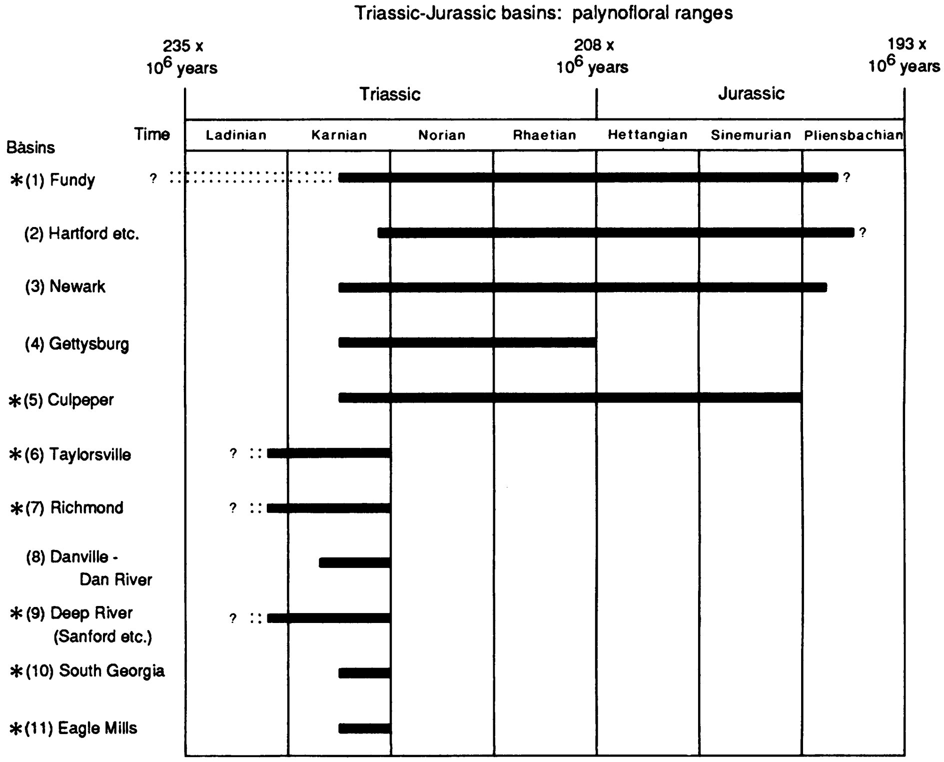


Fig. 1. Outcropping and buried Mesozoic fault-bounded rift basins of the eastern and southern margins of North America: the location of the newly dated sediments of the South Georgia Basin is indicated by the inset. The basins treated in this report are numbered: 1, Fundy; 2, Hartford-Springfield-Deerfield; 3, Newark; 4, Gettysburg; 5, Culpeper; 6, Taylorsville; 7, Richmond; 8, Danville–Dan River; 9, Deep River; 10, South Georgia; and 11, Eagle Mills (*17*).

Fig. 2. Present status of palynologically based age indications for rift basins of eastern North America. Asterisks indicate basins for which recent information has provided ranges not previously known, or has changed the age-interpretation (*18*). In both this figure and Fig. 4, the ranges depend on information from Europe, where spores and pollen ranges can be correlated with those of marine fossils. The precision of the correlation varies with the number of geological sections studied and also is presumably affected by differences in the time of extinction associated with the degree of geographic separation.



recognized). As stated earlier, the sediments of the Fundy Basin of Nova Scotia and New Brunswick are known from palynological evidence to date from mid-Karnian to well into the Early Jurassic (*5*). However, vertebrate paleontological evidence, as yet unsupported by palynology (*3*, figure 2; *8*), seems to show that some associated sediment of the Fundy Basin probably is even older than Ladinian, referable to the preceding Anisian Stage.

I have recently recovered palynoflorules from drilling cuttings at between 1373 m and 2184 m of the Essex 1 Lightsey well, Colleton County, South Carolina (*9*), in the buried South Georgia Basin (Fig. 1). Moderately abundant fossil spores and pollen of these samples include (Fig. 3, a to q) characteristic wide-ranging Late Triassic forms such as *Patinasporites densus* and *toralis*, plus others such as *Pyramidosporites traversei*, that do not occur before late Karnian, and forms such as *Platysaccus triassicus* that terminate in late Karnian (Fig. 4), making late Karnian the most probable age assignment for the sediments sampled (*10*).

Previously reported (*11*) palynofloras of the subsurface Eagle Mills Formation of

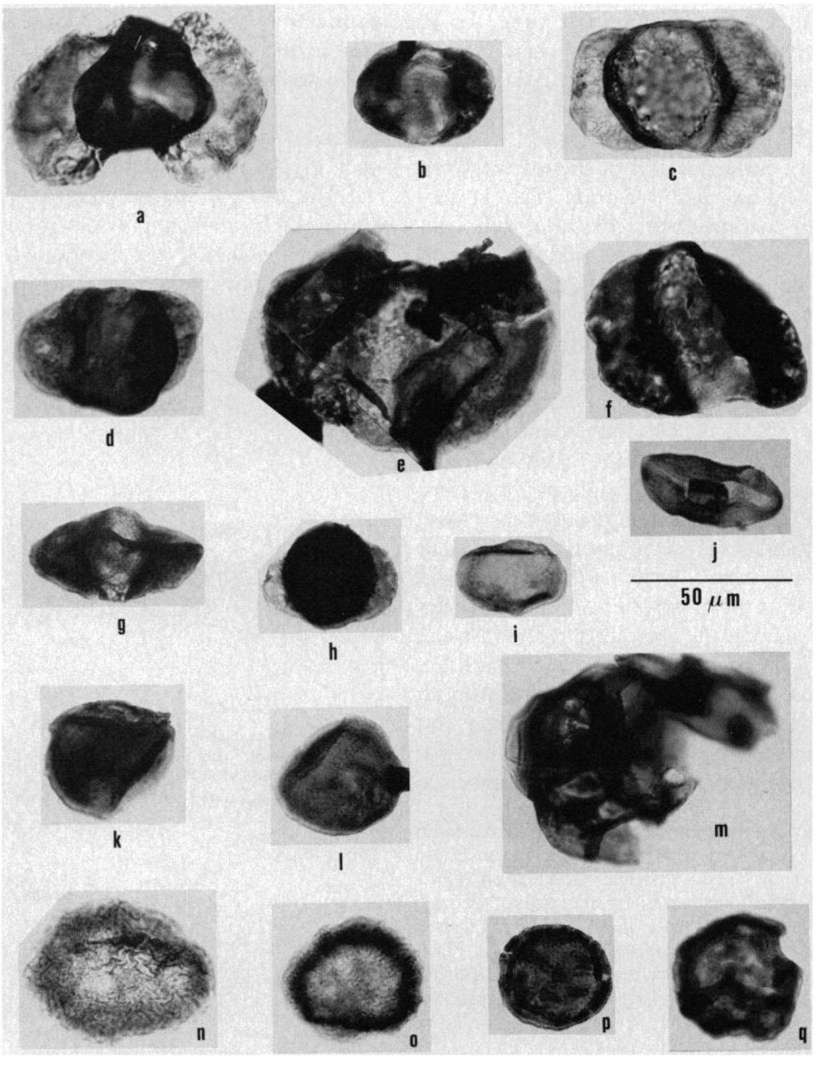


Fig. 3. Photomicrographs of some characteristic pollen from the buried South Georgia Basin prepared from well-cuttings obtained from about 1370 m in the Essex 1 Lightsey well, Colleton County, South Carolina (*19*). (**a**) *Platysaccus triassicus* (Mal.) Dunay & Fisher, proximal view; (**b**) *Klausipollenites gouldii* Dunay & Fisher, distal view; (**c**) *Alisporites thomasii* (Couper) Nilsson, proximal view in mid-focus; (**d**) *Alisporites* aff. *A. similis* (Balme) Dettmann, proximal view; (**e**) *Pityosporites oldhamensis* Dunay & Fisher, distal view, composite photomicrograph; (**f**) *Alisporites* aff. *A. toralis* (Leschik) Clarke, distal view; (**g**) *Klausipollenites* aff. *K. schaubergeri* (Pot. & Klaus) Jansonius, distal view; (**h**) *Triadispora* aff. *T. stabilis* Scheuring, distal view, corpus opaque; (**i**) *Cycadopites* sp., distal view; (**j**) *Cycadopites follicularis* Wilson & Webster, distal view; (**k** and **l**) *Praecirculina granifer* (Leschik) Klaus, a precursor circumpolloid form. The dark projection on the side of (**l**) is an unrelated piece of organic matter; (**m**) *Pyramidosporites traversei* Dunay & Fisher, broken specimen of obligate tetrad; (**n**) *Patinasporites densus* Leschik; (**o**) *Patinasporites toralis* Leschik; and (**p** and **q**) specimens displaying range of variation of *Camerosporites spissus* (Leschik) Dunay & Fisher.

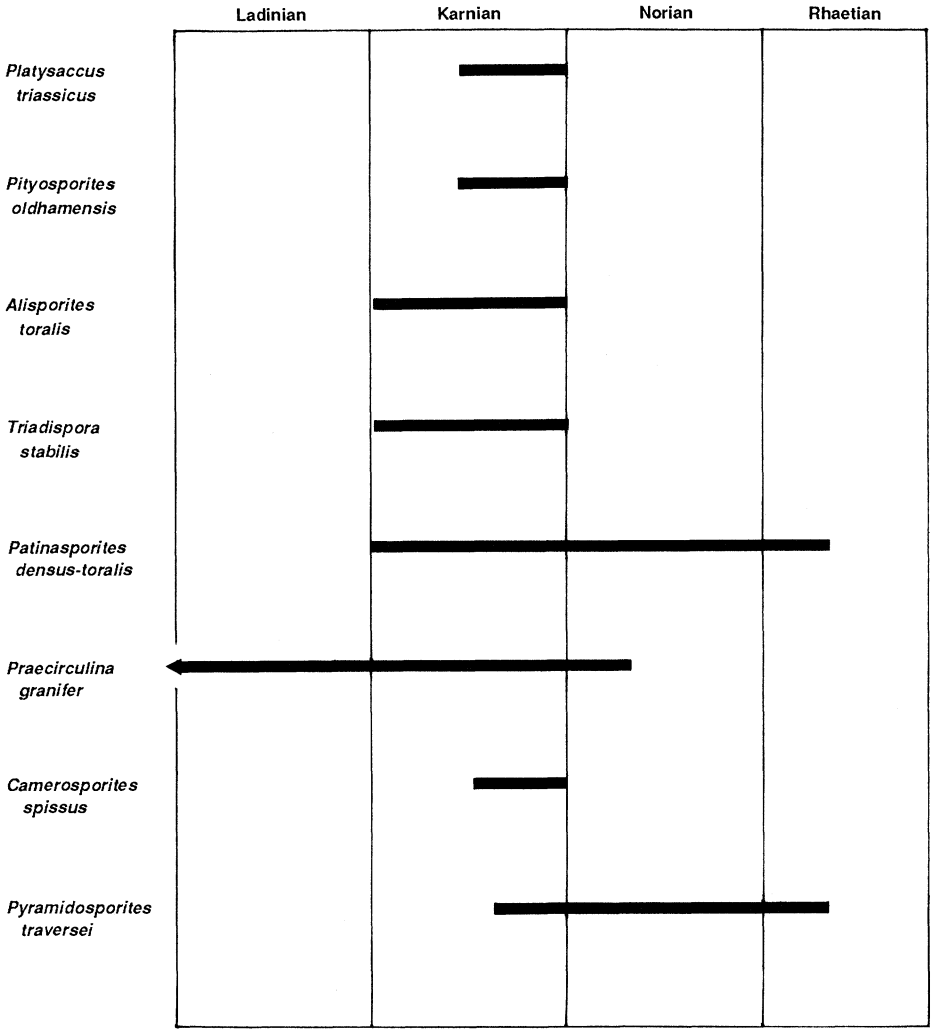


Fig. 4. Ranges of some significant sporomorph taxa encountered in Essex 1 well, South Georgia Basin (*10*).

Texas substantiate (Figs. 1 and 2) a mid- to late Karnian age for this sedimentary unit. The Eagle Mills, as the Newark Supergroup, apparently was deposited in a fault-bounded rift basin or basins (*12*). Drill-cutting samples from presumably Eagle Mills levels of a number of additional wells in Arkansas have now produced similar palynoflorules (*9*). There is evidence of further rift basins in northwestern Mexico, the sediments in which are dated provisionally as also Late Triassic (*13*).

The Newark basins evidently formed as rift basins, precursors by many millions of years of the separation of Africa from North America. The grain of the basins paralleled that of the Alleghenian (Variscan) orogenic belt (*14*). The palynological evidence shows (Fig. 2) that the rift basins first developed at least as early as the late Ladinian to early Karnian ages of the Triassic. Large-scale sedimentation apparently began first in some of the southern basins (Taylorsville-Richmond basins to the South Georgia Basin), though vertebrate evidence may show that the oldest sediment of all was formed in the Fundy Basin. Sedimentation apparently ceased in the southern basins (or less likely, all later sediments of the basins were removed) at or near the end of the Karnian (*15*), whereas sedimentation into the northern basins (Culpeper-Gettysburg-Newark, Hartford-Springfield-Deerfield, Fundy) continued for another 25 million to 30 million years. In at least some of the basins the sediments were deposited in very large lakes in cyclical patterns (*16*). On the basis of palynological dating it now seems that rifting as a precursor to the separation of the South American, North American, and other plates and the formation of the Gulf of Mexico began about the same time as the eastern rifting: Karnian age of the Triassic. The rifting apparently paralleled the structural grain of the Ouachita orogenic belt in the same way that the Newark basins paralleled that of the Appalachian (*12*). A chain of rift basins with initiation in the Karnian age of the Late Triassic can now be traced from offshore Newfoundland to northern Mexico. Palynofloras may also show changes in climatic regimes under which the producing vegetation lived near the sites of the continental breakup.

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North America Geology) scale. The palynological data are from the sources cited in (*11*) and (*17*), as interpreted here, except for new data (A. Traverse, unpublished) on the Culpeper and South Georgia basins. It should also be noted that Ediger (*7*) states that the oldest sediments of the Richmond-Taylorsville basins are of late Ladinian age. If this is correct, the oldest sediments of the Deep River Basin would also be Ladinian, as they contain similar palynofloras.

19. The shale samples studied were all prepared by HF maceration, $ZnCl_2$ solution (specific gravity 2.2) gravity separation, and Schulze's mixture (1:1) oxidation.
20. Various stages of this research were supported by NSF grants, most recently EAR-7905718. I acknowledge assistance of L. A. Wright and D. J. Nichols, who read and critiqued the manuscript. Present and former graduate students, especially B. Cornet, V. S. Ediger, R. J. Litwin, and M. B. Farley, gave constructive suggestions at various stages of the research. E. I. Traverse assisted with laboratory procedures.

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Swept Away: Resuspension of Bacterial Mats Regulates Benthic-Pelagic Exchange of Sulfur

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Filaments and extracellular material from colorless sulfur bacteria (*Beggiatoa* spp.) form extensive white sulfur mats on surface sediments of coastal, oceanic, and even deep-sea environments. These chemoautotrophic bacteria oxidize soluble reduced sulfur compounds and deposit elemental sulfur, enriching the sulfur content of surface sediment fivefold over that of deeper sediments. Laboratory flume experiments with *Beggiatoa* mats from an intertidal sandflat (Nova Scotia) demonstrated that even slight erosion of sediment causes a flux of 160 millimoles of sulfur per square meter per hour, two orders of magnitude greater than the flux produced by sulfur transformations involving either sulfate reduction or sulfide oxidation by benthic bacteria. These experiments indicate that resuspension of sulfur bacterial mats by waves and currents is a rapid mechanism by which sediment sulfur is recycled to the water column. Benthic communities thus lose an important storage intermediate for reduced sulfur as well as a high-quality bacterial food source for benthic grazers.

MICROBIAL MATS CONSISTING OF various sulfur bacteria are ubiquitous in marine intertidal and subtidal sediments and have gained recent attention as the base of the food web at deep-sea hydrothermal vents (*1*). Extracellular mucus, produced by microorganisms in the mats, binds the substrate, stabilizes the sediment surface, and influences the exchange of particles between the sediment and the water column (*2*). Despite the widespread occurrence of such biogenic mats, their effect on the exchange of nutrients between the sediment and the water column has rarely been considered (*3*). To examine this process we have used a laboratory flume to simulate tidal flow, sediment transport, and resuspension of benthic mats consisting mainly of the colorless sulfur bacteria *Beggiatoa* spp.

Beggiatoa oxidizes soluble sulfide to elemental sulfur and sulfate for chemoautotrophic fixation of CO_2 (*4*). Through gliding motility these bacteria maintain a vertical position in the sediment at the H_2S/O_2 interface (*4, 5*). In shallow waters, sulfur bacterial mats are abundant wherever organic enrichment occurs (estuaries, harbors, upwelling regions) (*1, 6*). On Eastern Passage sandflat, Halifax Harbor, mats are apparent as white sulfur coatings (up to 4 mm thick) on the sediment surface where reducing conditions and black, sulfide-rich sand occur (*7*) (Fig. 1).

Although the morphology of *Beggiatoa* and its production of extracellular slime have been studied in laboratory cultures (*6*), little is known about the intact mat structure and its potentially stabilizing effect on particle flux. Scanning electron microscopy (*8*) of intact samples from Eastern Passage demonstrated the presence of a complex mat structure with extensive connections of extracellular material between sand grains (Fig. 2A). A variety of organisms, detrital substrates, and flocculation reactions contribute to the amorphous appearance of the mat (*8, 9*). Both filamentous and circular growth forms (*6*) of the *Beggiatoa* trichomes were observed (Fig. 2, B through D).

In an active sulfuretum, internal deposition of elemental sulfur by *Beggiatoa* (*6*) allows use of total sediment sulfur as a tracer of these bacteria (*10*). We first examined the effects of sediment transport on benthic sulfur fluxes in a "control" sediment sample lacking *Beggiatoa* mats (April). Using a small box corer (18 by 18 cm), we collected undisturbed field cores from Eastern Passage after a storm. These cores had black reducing sand at the surface with some tan oxidized sand at ripple crests; ripples were 6 cm in wavelength and 0.5 cm in crest-trough height. The box core sample was placed in the fitted corewell of a flow-through laboratory flume, the sediment surface flush with the flume bed (*11*). Flowing water, measured with thermistor anemometers (*11*), was gradually applied until the initiation of sediment movement on the ripple crests (critical friction velocity, $u_{*\mathrm{crit}}$). Gentle erosion for 0.5 hour produced only a minor change in the total sulfur content (*12*) of the upper millimeters of sediment (Table 1). When sulfur mats were absent, erosion exposed underlying sediments, which had a sulfur content similar to that of surface sand (for example, due to iron sulfides), and no flux was apparent.

Cores with similar ripples collected after extended calm weather (May) had a white surface and about twice the total sulfur content of post-storm black sediments (Table 1). Later summer samples (July) of the bacterial mats showed that sulfur enrichment of surface sediments was undoubtedly due to *Beggiatoa* mats; mat-free sand from surface-oxidized sediments or deeper black sediments lacked high concentrations of sulfur (Fig. 3). When intact sediment cores with mats were eroded in the flume, white aggregates of sand, mucus, and *Beggiatoa* in the upper 2 to 3 mm of sand were visibly resuspended.

Erosion caused the severance of bacterial trichomes because sediment transport disrupted grain-grain contacts (Fig. 2D). Almost 50% of the sulfur content was resuspended (*5*), creating a mottled black-white surface and exposing an underlying reducing layer similar in sulfur content to the mat-free April core (Table 1). Variation in ripple morphology may affect $u_{*\mathrm{crit}}$ more than the binding action of microbial mucus (*2, 8*). However, the effect of sediment transport on resuspension of *Beggiatoa* mats was consistent for both cores. Even mild erosion in the flume (that is, nonstorm transport) produced major changes in total sediment sulfur similar to those caused by a storm event in the field (Table 1).

On the basis of an erosion depth of 3 mm and a bulk density for the sediment of 1.39 g cm^{-3}, the resuspension of *Beggiatoa* from cores in the flume is equivalent to a sulfur

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