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BAHAMIAN "WHITINGS" AS TURBULENT-FLOW PHENOMENA

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ABSTRACT

Highly turbid water parcels of problematic origin, known as whitings, are commonly observed within shallow-marine environments of the Great Bahama Bank. The physical characteristics of whitings are consistent with predicted and observed characteristics of turbulent-flow systems. Specifically, whitings may be the observable manifestation of the bursting (ejection-sweep) cycle of turbulence production at flow-boundaries. The bursting process has been identified as the source of turbulence emanating from flow-boundaries and can generate velocity excursions which deviate from mean flow velocity by a factor of 4. Published data for mean tidal-current velocities within the central Great Bahama Bank range from 8 to 50 cm s^{-1}. Thus, maximum predictable velocities during the bursting process will range from 32 to 200 cm s^{-1}, quite in excess of empirically determined threshold sediment-transport velocities (<30 cm s^{-1}). In addition, 4-fold velocity excursions during turbulent flow produce 16-fold increases in lift force at the sediment-water interface, enhancing bottom-sediment destabilization, particle entrainment and suspension. The visible, roiling nature of whiting water parcels is believed to be the expression of the above turbulent flow processes on Great Bahama Bank. It is also notable that turbulent boundary-layer flow becomes organized into alternating low- and high-velocity "streaks", giving rise to alternating zones of active sediment-resuspension and deposition. This pattern of fluid movement may account for the development of subparallel digitations frequently observed within whitings. Supplemental evidence supporting a bursting/resuspension origin for whitings includes ^{14}C measurements which yield relatively old ages (ca. 200 yrs) for calcium carbonate collected within whitings.

INTRODUCTION

The occurrence of isolated, turbid water parcels among the clear, shallow waters of tropical carbonate platforms and banks is a frequent event referred to as a "whiting" (Figs. 1a-c). Whitings contain as much as 21 mg l^{-1} of fine-grained (<8 um), suspended carbonate particles (dominantly aragonite) which have been variously interpreted as "fish-muds" (fine-grained sediments stirred into suspension by the activity of bottom-feeding fish), products of active inorganic-carbonate precipitation within the whiting water parcel (Cloud, 1962a and b; Shinn, *et al.* 1989), incidental carbonate precipitation related to rapid CO_2 uptake during algal blooms (Robbins & Blackwelder, 1990) or as fine-grained bottom-mud resuspended by physical processes (Broecker & Takahashi, 1966; Morse *et al.*,1984). However, any hypothesis for the origin of these turbid water parcels on Great Bahama Bank must identify processes which can account for 1) the observed temporal frequency of whitings and 2) the observed geographic distribution of whitings within bank-top waters.

The temporal frequency of whitings on Great Bahama Bank is not well known. Whitings have been observed in all seasons and in all weather conditions on the bank-top. Significantly, whitings are known to originate and persist during extended periods of light winds, thus excluding wind-induced turbulence as a primary component in whiting origination.

The geographic distribution of whitings on Great Bahama Bank is non-random (Fig. 2). Superimposed on Purdy's (1963) well-known map of Bahamian sediment facies, it can be seen that >90% of whitings occur over pellet-mud or mud sediment facies (data plotted from satellite photographs obtained intermittently between 1972-1975; J.W. Morse,personal comm.).

Fig. 1a: Photograph of typical *whitings in the* Bahamas. Note that the whitings occur as distinct bands of high- turbidity water within the relatively clear waters of the bank top (photo by A.C. Hine, Univ. of S. Florida).

Fig 1b: Large whiting photographed on Little Bahama Bank. Dimensions of this particular whiting are several kilometers in length and breadth; photo by A.C. Hine, Univ. of S. Florida).

Fig. 1c: View of the active front of a whiting showing development of subparallel, digitate zones of high- and low-turbidity. This morphology is a common feature of whitings and may result from organization of boundary- layer flow into alternating high- and low-velocity streaks (see Fig. 7; photo by A.C. Neumann, Univ. of N. Carolina).

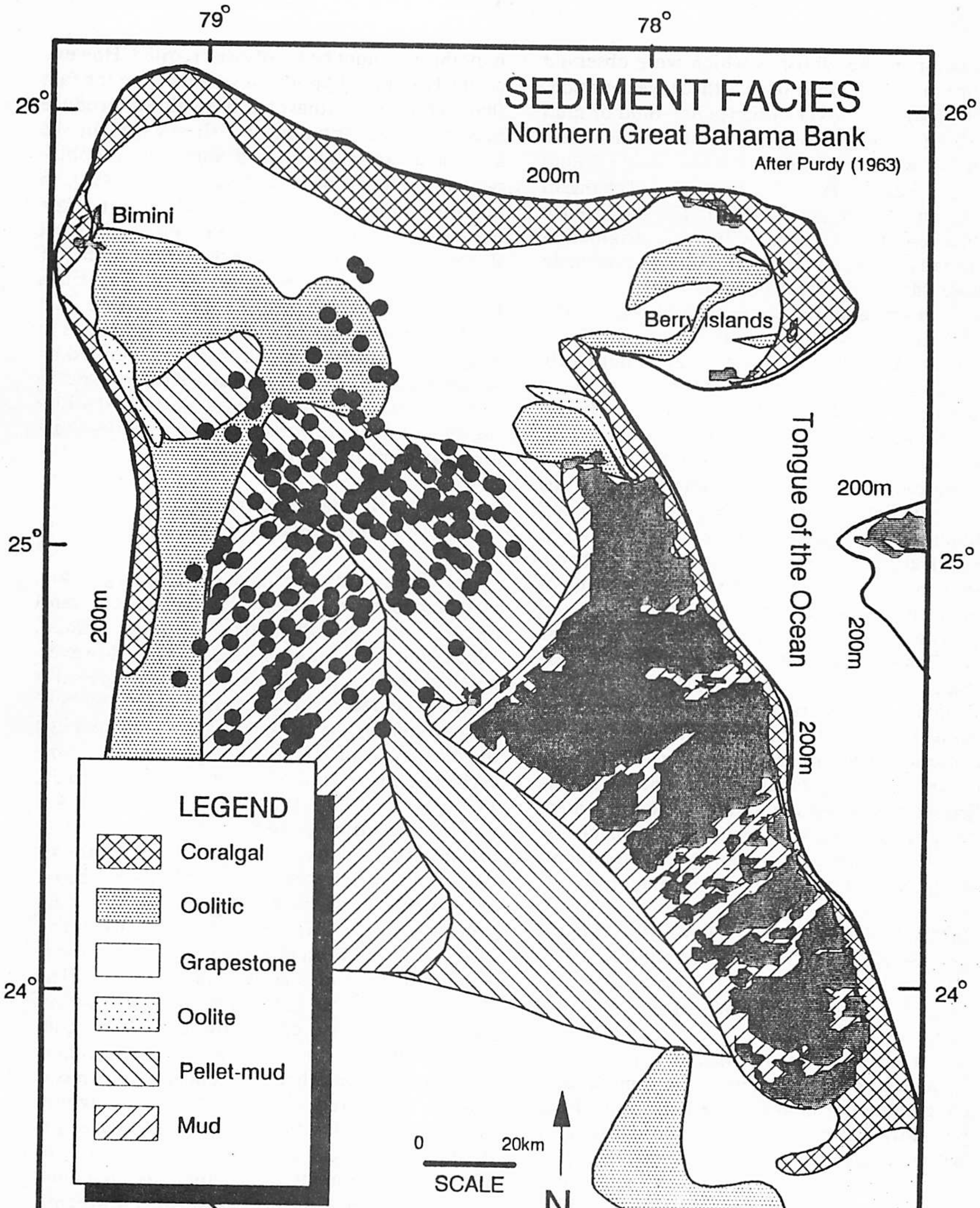

Fig. 2: Sediment facies of the northern Great Bahama Bank with whitings (closed circles) observed from satellite photographs (Morse *et al.* 1984) and from eye-witness accounts (Shinn *et al.* 1989) superimposed. Notice that 90% of whitings occur over pellet-mud or mud sediment facies. The occurrence of a small number of whitings north of the major pellet-mud accumulation is coincident with Mackie Bank, an anomalously shallow, high-energy, linear sediment ridge of undetermined origin. The absence of whitings south of 24° 30' N latitude is due entirley to absence of data from this region, and should not be construed to indicate that whitings do not occur there (sediment facies map after Purdy 1963).

Indeed,of the 40 whitings which were observed by Shinn *et al.* (1989) over a three-year period, 39 (97.5%) occur over either pellet-mud or mud sediment facies. This is the same region where whitings were observed by Smith (1940), Cloud (1962a), Purdy (1963), Broecker & Takahashi (1966) and Morse *et al.* (1984). The persistence of this region as an area of whiting origination over many years is a notable feature of carbonate sedimentation on Great Bahama Bank.

Hydrographic, chemical and sedimentological factors associated with water parcels on the central bank-top have been intensively studied for at least 50 years. A review of these data (Smith 1940; Cloud 1962a and b; Purdy 1963; Broecker & Takahashi 1966; Morse *et al.* 1984) provides substantial insights into the whiting enigma on Great Bahama Bank. In this paper, available hydrographic, chemical and sedimentological data are reviewed from a theoretical perspective to illustrate the probable effects of hydrodynamic processes (turbulent bursts) on sediment stability, entrainment and suspension during water movement over the Great Bahama Bank. It is suggested that these physical processes are sufficiently common (indeed, they are characteristic of turbulent-flow systems) to account for both the observed spatial distribution and temporal frequency of whitings. However, empirical testing of the whiting mechanism proposed herein will require an integrated, interdisciplinary view of various physical, chemical, sedimentological and biological components of the Great Bahama Bank environment.

SUMMARY OF ALTERNATIVE "WHITING" GENERATION MECHANISMS

Fish-muds and Whitings

It has long been believed that whitings are generated by the activity of bottom-feeding fish (e.g. mullet or bonefish). Indeed, this idea is deeply entrenched in the "common wisdom" of the Bahamian people. According to this hypothesis, schools of bottom-feeding fish ingest large quantities of bottom sediment, extract the edible components and eject remaining sediment into the water column through their gills to generate whitings. Fish such as mullet and bonefish are known to feed in this manner and the fish-mud hypothesis cannot be totally discredited. However, the fish-mud hypothesis suffers from the fact that no credible witness has been able to produce tangible documentation of fish engaged in the act of generating whitings, despite rather sophisticated attempts to do so (Shinn *et al.* 1989). In addition, there are presently no data to indicate that fish occur in appropriate numbers on Great Bahama Bank to account for the large number of whitings which can be observed at any time. Finally, it taxes the imagination to believe that the largest whitings (up to several kilometers in length and breadth; Fig. 1b) can be generated by schools of fish. Certainly, such large schools as would be necessary to produce the largest whitings would be noteworthy features on the shallow platforms of the Bahamas.

Large scale, Inorganic Precipitation Events

Several authors have favored large scale, instantaneous precipitation events as the most likely source of Bahamian whitings (Cloud, 1962a and b; Shinn *et al.*, 1989). However, detailed studies of the carbonate system relative to the extended residence time (up to 250 days) of seawater on the bank-top have demonstrated the influence of kinetic factors in controlling carbonate precipitation (Broecker & Takahashi, 1966; Morse *et al.*, 1984). In view of observed kinetic limitations, large scale instantaneous precipitation events resulting in whitings are not likely. In addition, chemical gradients indicative of on-going, instantaneous carbonate precipitation (e.g. measurable changes in pH, alkalinity, PCO_2) have not been observed between whiting-water parcels and adjacent clear waters. This suggests that Great Bahama Bank waters are not particularly well suited to whiting-scale inorganic precipitation and that whiting phenomena must result from other than chemical processes. Finally, measured ^{14}C activities of aragonite needles collected within whitings yield ages between 200-300 yrs, consistent with ^{14}C activity of bottom sediments. Since there is no known isotopic fractionation mechanism during precipitation which could account for this relation, it provides indirect evidence that the majority of aragonite within whitings is resuspended bottom sediment.

SCHEMATIC DIAGRAM OF FLOW STRUCTURE AND VELOCITY PROFILE FOR SMOOTH & ROUGH BOUNDARIES

(From Daily & Harleman, 1966)

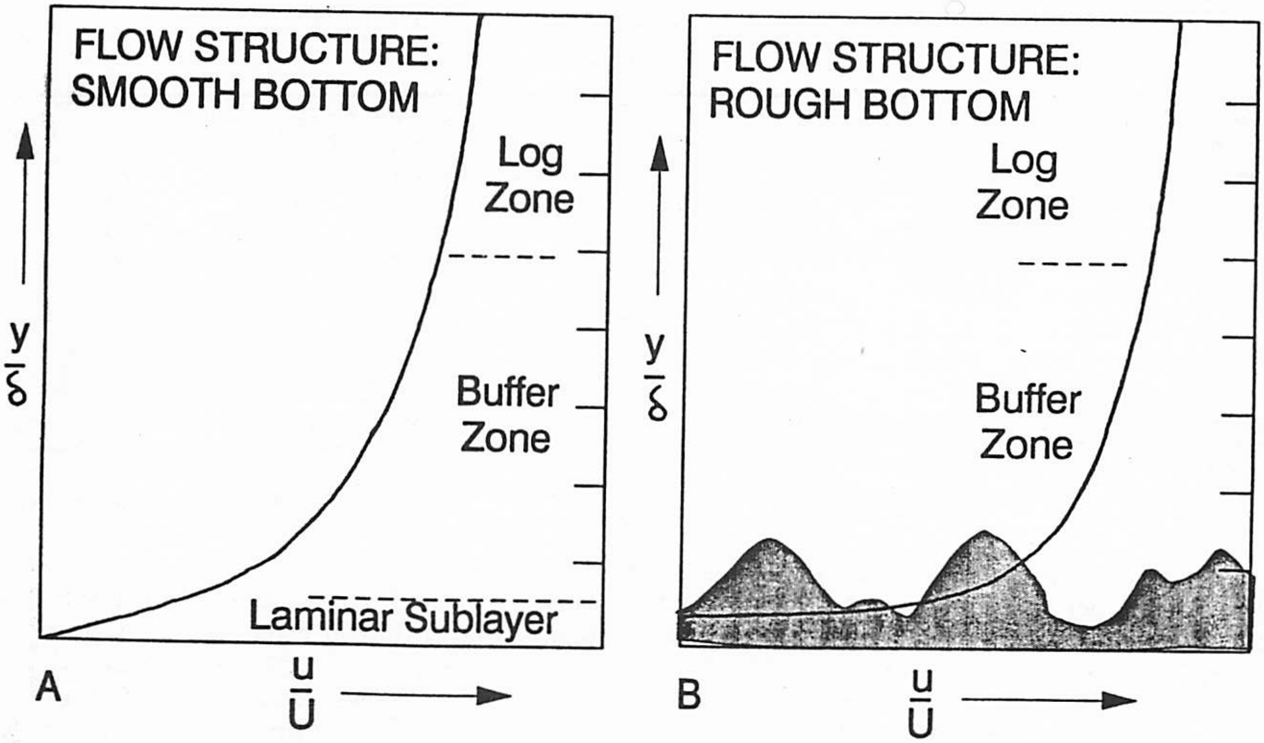

Fig. 3: Schematic diagram of flow structure and velocity profile for smooth & rough boundaries. A=Boundary layer structure over a smooth bottom. **B**=Boundary layer structure over a rough bottom. In each case, the velocity profile is idealized. The horizontal axis shows instantaneous velocity (**u**) as a proportion of mean velocity of flow (**U**). The vertical axis represents relative position within boundary-layer as the proportion of height above wall (y) vs. boundary layer thickness (δ). Note that representation of the dependent and independent variable in this way results in dimensionless values, implying that absolute scaling phenomena are essentially irrelevant in defining the structure of the boundary layer. Also, note that the laminar or viscous sublayer may be missing altogether during flow over rough walls (**B**). Not shown on this figure is the wake region, which occupies up to 80% of the boundary layer thickness (from Daily & Harleman 1966).

Biologically Induced Precipitation

It has been proposed that rapid CO_2 uptake during phytoplankton blooms induces spontaneous, large scale precipitation of calcium carbonate to produce whitings (Robbins & Blackwelder, 1990). However, PCO_2 measurements by Morse *et al.* (1984) indicate that for bank-top waters, PCO_2 is generally 1.5 times higher than in open-ocean waters, agreeing with estimates of Traganza (1967) that CO_2 production through organic matter respiration and carbonate precipitation on the bank-top outpaces CO_2 removal through photosynthesis and air-sea gas exchange. In addition, no data are currently available to indicate that isolated, local blooms of sufficient magnitude occur with the required frequency to account for the observed distribution of whitings. In fact, Smith (1940) and Cloud (1962a) showed that bank-top waters are nearly devoid of essential nutrients, especially phosphate (usually <1umol l^{-1}; Cloud, 1962a). It is difficult to imagine sustained, large scale algal productivity in such nutrient-deficient waters. The biologically-induced-precipitation hypothesis may warrant additional study, but until a plausible nutrient cycle is identified on the bank-top, it does not appear reasonable.

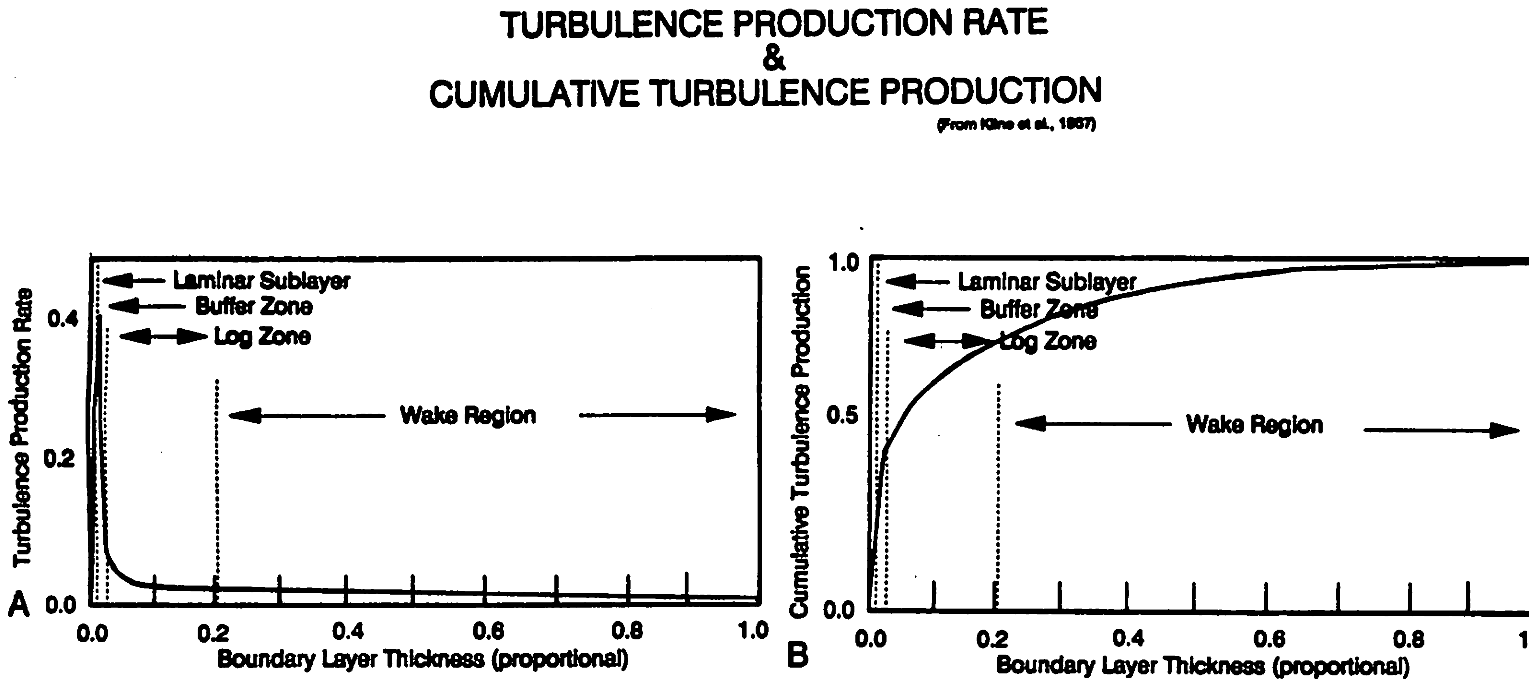

Fig. 4: Turbulent production rate & cumulative turbulence production. A=Turbulent energy production rate per unit volume in a typical boundary layer. Note the dramatic peak in turbulence production associated with the innermost region of the boundary layer (buffer layer) and the virtual absence of turbulence energy contribution from other regions (from Kline *et al.* 1967). B=Cumulative turbulent energy production rate in a typical boundary layer. This plot shows clearly that ca. 50% of turbulent energy production in the boundary layer is contributed by dynamic processes within the relatively thin buffer region. Note again that the large wake region contributes relatively little turbulent energy to the system (from Kline *et al.* 1967).

WHITINGS AS TURBULENT-FLOW PHENOMENA

Among the remaining hypotheses which have been proposed to explain the occurrence of whitings on the Great Bahama Bank, the suggestion that whitings result from physical resuspension of fine-grained bottom-muds has never been adequately evaluated. As a result of relatively crude measures of tidal-current flows (Shinn *et al.*, 1989), there has developed a general consensus that water movement on the banktop is too sluggish to provide the required energy for sediment resuspension. In the following discussion, some elementary principles of the structure and dynamics of turbulent flow are outlined, and the relation of these principles to sediment entrainment and suspension are presented. It is intended that this discussion will provide the theoretical foundation needed to consider whitings as turbulent-flow phenomena. In addition, it is important to note that much of the knowledge of turbulent-flow systems is derived from experimental studies using flumes. As such, the scale of experimentally observed turbulent-flow phenomena is likely much smaller than that to be expected in natural systems. However, fluid dynamicists are well aware that processes of fluid flow display a high degree of self-similarity. In fact, the general tradition of representing data in fluid dynamic studies as dimensionless values implies that absolute-scaling factors are largely irrelevant in the application of theoretical constructs to natural systems (Middleton & Southard, 1984). On this basis, it is suggested that the physical characteristics of whitings are consistent with predicted and observed features of experimental turbulent-flow systems, only on a larger scale. Moreover, these turbulent-flow processes are sufficiently common to account for the geographic and temporal distribution of whitings on Great Bahama Bank.

STRUCTURE OF TURBULENT BOUNDARY LAYERS

Numerous investigations of the structure of turbulent flow have revealed that turbulence production is intimately related to flow characteristics near fluid and solid boundaries (Daily & Harleman, 1966). Indeed, the structure of the boundary layer has been described in some detail (Kline *et al.*, 1967) as a result of flow visualization experiments (Kline *et al.*, 1967; Kim *et al.*, 1971; Grass, 1971). These experiments show that boundary layers can be subdivided into several regions which display characteristic flow behavior (Fig. 3; Daily & Harleman, 1966). For a smooth boundary, there exists a narrow region where viscous forces dominate and flow is laminar (viscous or laminar sublayer, Fig. 3a). For water (relatively low viscosity), this region is generally exceedingly thin (Kline *et al.*, 1967) over a smooth boundary and may be missing altogether over rough boundaries (Fig. 3b; Daily & Harleman, 1966). Adjacent to the viscous sublayer there is a zone in which laminar flow decays rapidly into intense turbulence (the so-called buffer zone, Figs. 3a & b, 4a) which appears to contribute up to 50% of the cumulative turbulence production in the system (Fig. 4b; Kline *et al.*, 1967). Finally, there are two broad regions (logarithmic zone and wake zone) over which mean flow-velocity increases geometrically to its maximum magnitude. It is interesting to note that the wake region occupies up to 80% of the boundary layer, yet contributes <20% of the total turbulence production (Fig. 4b; Kline *et al.*, 1967). Thus, concentration of current measurements within this region are unlikely to reveal significant flow anomalies associated with turbulence production. Indeed, flow visualization experiments (Kline *et al.*, 1967; Kim *et al.*, 1971) confirm the dominance of the near-wall region (buffer zone) in turbulence production. These studies have permitted additional detailed descriptions of the process of turbulence production by intermittent low-velocity ejection/high-velocity sweeps within the fluid (referred to as "bursting").

DYNAMICS OF THE "BURSTING" CYCLE

Flow visualization studies by Kim *et al.* (1971) were the first to examine the detailed sequence and structure of the burst cycle in turbulent flow. Their observations indicated that virtually all turbulence production within boundary layer flows occurred during the burst cycle and established the importance of understanding the dynamics of bursting.

The burst cycle is illustrated by sequential velocity profiles (Fig. 5) recorded during flow visualization experiments of Kim *et al.* (1971). Initially, the boundary layer velocity field conforms relatively well to the ideal, logarithmic profile typical of turbulent-flow systems (profile "h", Fig. 5). Bursting begins with development of a prominent velocity defect, visible as a velocity inflection near the laminar sublayer/buffer zone boundary (profile "g", Fig. 5). Lifting of this low-velocity (low-momentum) fluid parcel into the stream flow can be observed on the time series of instantaneous velocity profiles (profiles "f" through "b", Fig. 5). Following ejection of this low-velocity fluid parcel from the boundary region, the instantaneous velocity profile (profile "a", Fig. 5) shows an in-rush (sweep) of higher velocity fluid, presumably derived from high-velocity streaks adjacent to the lifted low-velocity fluid. This in-rush of higher velocity fluid partially stabilizes the instantaneous velocity profile and the bursting cycle (low-velocity ejection/high-velocity sweep) is completed.

Bursting phenomena can also be identified as intermittent, large-amplitude oscillations in time series plots of instantaneous boundary layer flow-velocity (Fig. 6). It is particularly important to note the magnitude of velocity fluctuations within the burst cycle, as entrainment and suspension of sediments from the boundary may be significantly influenced by these fluctuations (Middleton & Southard 1984). Grass (1971) reported that velocity excursions can be as large as 3 to 4 times the mean flow velocity, even in relatively slow- moving fluids. For example, in a mean current of 15 cm s^{-1} it would be common to experience transient excursions as large as 45 - 60 cm s^{-1}. In addition, flow over rough boundaries will create lift forces (Einstein and El-Samni 1949) which are related by:

$$\Delta P = C_L(\rho/2)\mathbf{u}^2$$

where ΔP is the vertical pressure change, C_L is the lift coefficient (constant), ρ is fluid density and **u** is instantaneous velocity. Thus, 3- to 4-fold increases in instantaneous velocity associated with bursting will result in 9- to 16-fold increases in the lift force affecting the wall region. Such increases most certainly influence

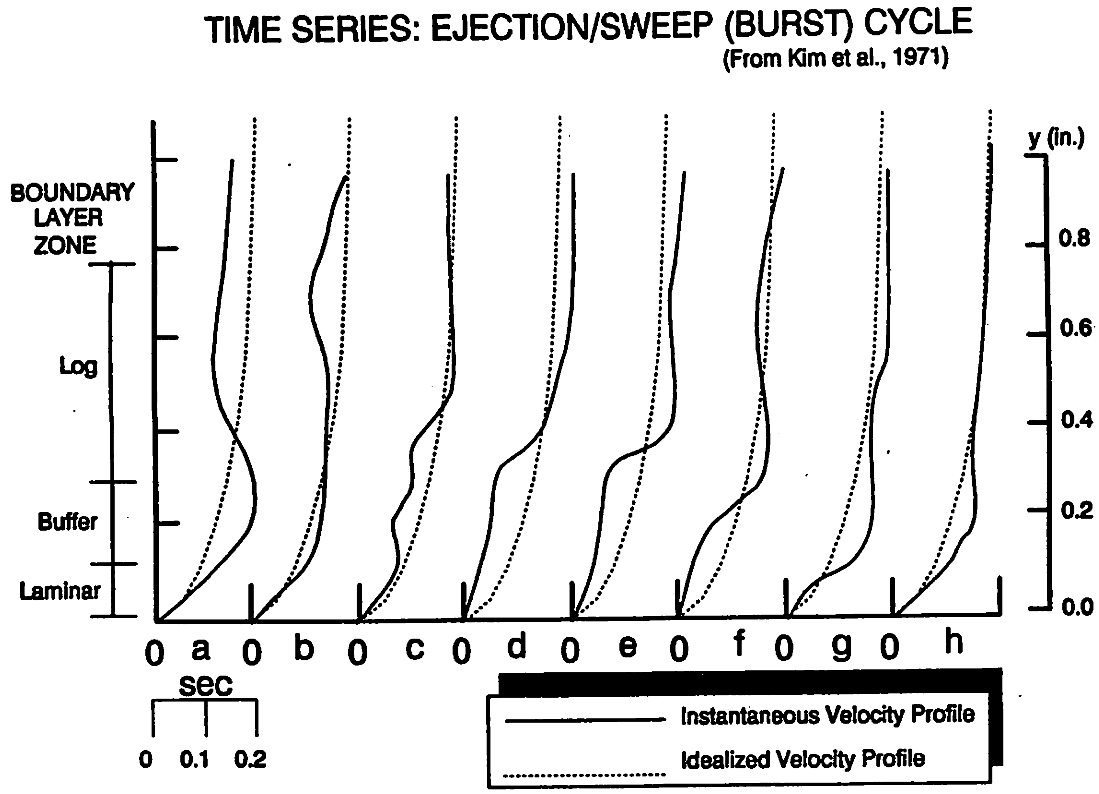

Fig. 5: Time series: measured instantaneous velocity. Vertical axis on right is distance above flume bottom (y) in inches. Horizontal axis divided into 8 profiles taken at 0.2s intervals. Time zero is represented by profile "h". Examination of these plots from right to left shows low-velocity streak lifting (ejection phase of bursting) visible as a velocity inflection propagating upward from the wall region (g through b). The lifting (ejection) phase is followed abruptly by in-rush of high-velocity fluid (sweep phase of bursting) visible as a prominent bulge in the last velocity profile (a). It is during this phase of bursting that instantaneous velocity excursions as much as 4 times mean flow may occur. Following this phase of the bursting event, the instantaneous velocity profile acquires a shape similar to the mean velocity profile until the next bursting event begins (from Kim *et al.*, 1971).

the ability of even moderate flows to entrain and suspend sediments. In fact, Gordon (1975) measured naturally occurring bursts in a tidal estuary and found that the burst contribution to bottom stress, turbulence production and sediment transport was significant. Apparently, the effect of bursting was manifest as a 4- to 5-fold increase in Reynolds stress, resulting in intermittent sediment transport by traction and suspension.

BURSTING AND THE ORIGIN OF BAHAMIAN WHITINGS

Demonstration of the significance of burst cycles in turbulence production (Kline *et al.* 1967; Kim *et al.* 1971; Grass 1971) and the intermittent transport of sediment (Heathershaw 1974; Gordon & Dohne 1973; Gordon 1975) is an important contribution toward understanding the whiting phenomenon in the Bahamas. Whereas much of the knowledge of fluid boundary layer structure and dynamics is derived from experimental flume studies, integration of these ideas with available chemical, physical and sedimentological data for whitings is highly suggestive of an explanation of whitings as resuspended fine-grained bottom sediment. Indeed, many of the observed physical characteristics of whitings are consistent with predicted and observed patterns of turbulent-flow systems.

For example, the visible, roiling nature of whiting water parcels may be the expression of the bursting process as water moves across the Great Bahama Bank during the tidal cycle. Also, many whitings display subparallel, digitate zones of turbidity along their active fronts (Fig. 1c). This feature is consistent with organization of

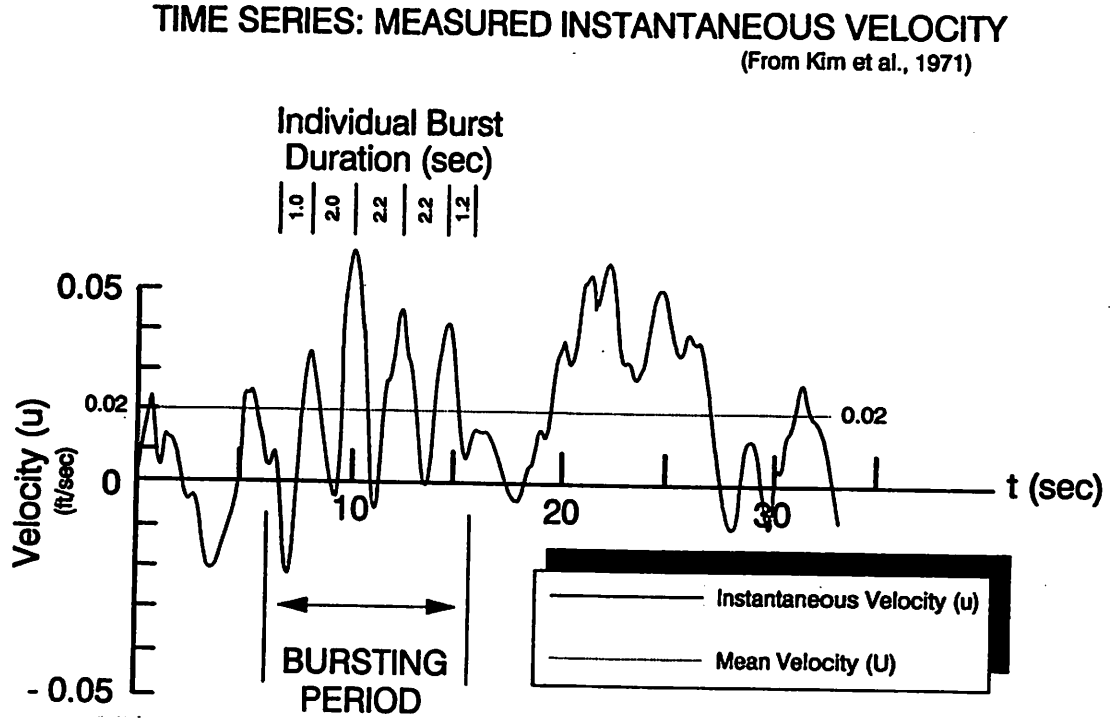

Fig. 6: Time series: measured instantaneous velocity. Bursting phenomena can be identified as closely spaced, large magnitude excursions about mean velocity (0.02 ft s^{-1}). Maximum velocity excursions in this example are about three-times the mean velocity for this relatively low overall flow. Reported excursions 3 to 4 times larger than mean velocity are known for faster moving fluids (U = 14.5 cm s^{-1}; Grass 1971). In addition, notice that the bursting period has duration of 8 - 10 seconds during which several pulses of high-velocity fluid may be observed. Numbers above observed burst period represent duration of individual bursts in seconds. Note that individual bursts are not only frequent, but also of large magnitude (from Kim *et al.*, 1971).

boundary layer flow into alternating low- and high-velocity "streaks" observed in transverse (across-stream) velocity profiles during flume experiments (Fig. 7; Kline *et al.* 1967). Such transverse or "spanwise" velocity fluctuations were correlated with alternating regions of sediment transport and redeposition in these experiments and it is suggested that alternating high-turbidity/low-turbidity bands within whitings result from similar flow organization patterns.

Mean tide-dominated flow velocities (U) over Great Bahama Bank in the region of abundant whitings are reported to range from 8-50 cm s^{-1} (Smith 1940; Shinn *et al.* 1989; Cloud 1962a), similar to velocities used for laboratory experiments of turbulent-flow over smooth and rough boundaries (Grass 1971). For this range of velocities, peak flow rates during bursting ($\simeq$ 4U) may be expected in the range 32-200 cm s^{-1}.

These velocities are capable of suspending all particles smaller than 0.125mm, provided such a size-range is available in the sediment (Sengupta 1979). Consideration of the geographic distribution of whitings (Fig. 2) with respect to sediment textural data (Table 1; Purdy, 1963) demonstrates the importance of this observation. It is obvious from Figure 2 that whitings are significantly correlated with pellet-mud and mud sediment facies and notably absent from other regions of the Great Bahama Bank. The average weight percents of sediment <0.125mm in pellet-mud and mud facies are 42.8% and 61.7% respectively. The weight percent of sediment <0.125mm in remaining bank-marginal facies (coralgal, oolitic, grapestone) is generally less than 5%. Thus it would appear that whiting frequency is related not only to available fluid turbulence, but also to the availability of fine-grained sediment.

WHITINGS AND THE CONCEPT OF ENVIRONMENTAL ENERGY "FACIES"

The concept of "environmental energy facies" is useful in describing the observed whiting distribution on Great Bahama Bank. "Environmental energy" may be defined in qualitative terms as the physical energy flux contributed by tidal-currents, wind and waves

SCHEMATIC CROSS-STREAM VELOCITY TRANSECT
(From Kline et al., 1967)

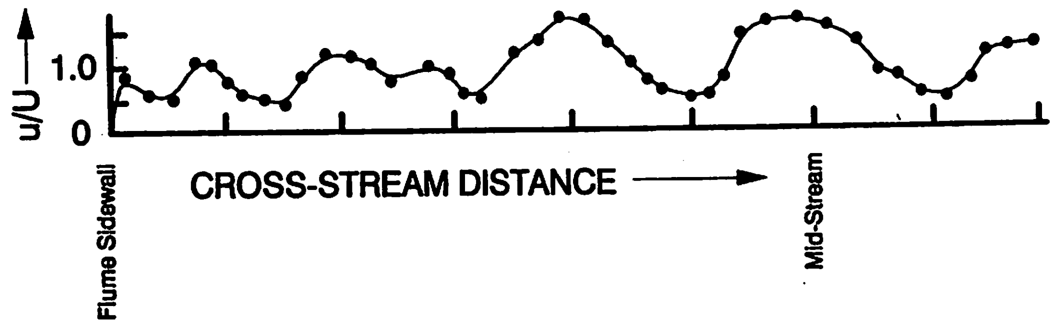

Fig. 7: Schematic cross-stream velocity transect. Instantaneous transverse (i.e. across-stream) velocity profile in experimental boundary layer flow shows organization into alternating low- and high-velocity "streaks" which are subject to broad temporal oscillations. Vertical axis is relative velocity expressed as the ratio of boundary layer velocity (u) to total mean velocity (U). Horizontal axis is schematic span-wise distance.(from Kline *et al.* 1967).

TABLE 1

Textural Characteristics of Bahamian Carbonate Sediments

Great Bahama Bank

(From Purdy, 1963)

FACIES	GRAIN SIZE	
	% > 0.125mm	% < 0.125mm
CORALGAL	89.2	10.8
OOLITIC	95.0	5.0
GRAPESTONE	95.5	4.5
OOLITE	98.1	1.9
PELLET-MUD	57.2	*42.8*
MUD	38.3	*61.7*

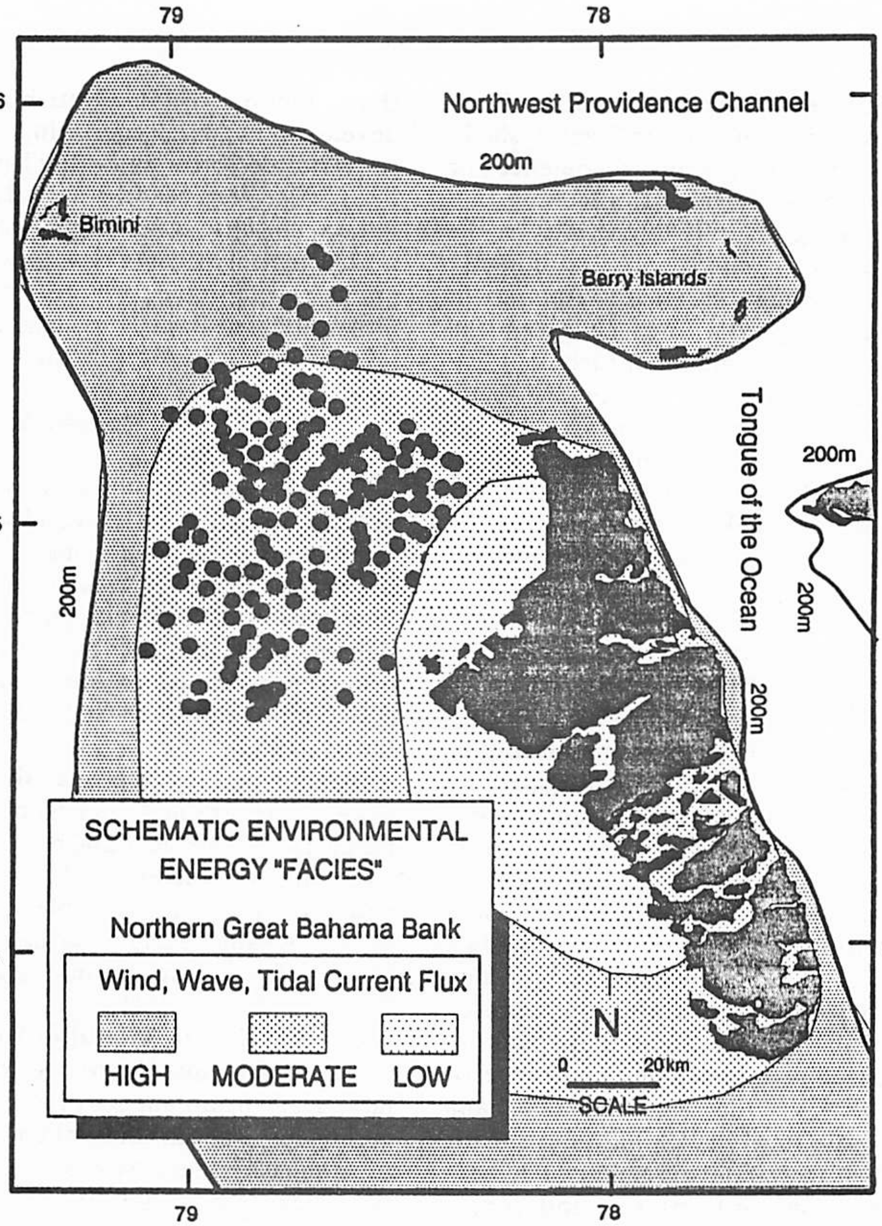

Fig. 8: Schematic environmental energy "facies", northern Great Bahama Bank. Environmental energy is defined as tidal- current, wind and wave flux. Energy flux near bank margins is high but decreases progressively across the bank interior toward the leeward coast of Andros Island. Note that whitings (closed circles) are uncommon near bank margins where energy flux is high. Although bank-marginal environments are sufficiently turbulent for whiting formation, bottom sediments in bank-marginal facies are nearly devoid of fine-grained carbonate. Near Andros Island, carbonate mud is abundant in bottom sediments, but whitings are rare because deposition occurs in the energy shadow created by the island. Whitings are only common on the central bank interior where energy flux is sufficiently high and carbonate mud sufficiently plentiful such that resuspension can occur (after Purdy 1963).

within a depositional environment. On Great Bahama Bank, environmental energy diminishes from bank margins toward the bank interior (Fig. 8; Purdy, 1963). Bank-marginal depositional environments are certainly sufficiently turbulent to resuspend bottom sediments, yet whitings are rare in these settings because bottom-sedi ments are virtually devoid of fine-grained carbonate (Table 1). Whitings are also uncommon over a bank-top area close to the western shore of Andros Island. Here, carbonate-mud is abundant, but deposition occurs in the "energy shadow" created by the island. Thus, turbulence for sediment resuspension is generally lacking (i.e.

of Andros Island. Here, carbonate-mud is abundant, but deposition occurs in the "energy shadow" created by the island. Thus, turbulence for sediment resuspension is generally lacking (i.e. environmental energy flux is low). Only on the central bank interior is energy flux sufficiently high and carbonate mud sufficiently abundant for whitings to originate. Indeed, given the availability of carbonate mud and turbulent energy over a broad area on the central bank interior, it is somewhat astonishing that the entire bank-top is not continuously "whited" with suspended sediment. The explanation for the absence of whole-bank whiting appears to lie in the known bottom-stabilizing influence of subtidal algal mats.

BIOLOGICAL INFLUENCES ON BOTTOM-SEDIMENT STABILITY

Subtidal mats formed of communities of algae and cyanobacteria were investigated by Neumann *et al.* (1970). Results of underwater flume experiments indicated that minimum velocities necessary to induce sediment erosion and suspension were significantly larger (2 to 5 times) when bottom sediments were inhabited by these communities. It is important to note that whereas subtidal algal mats are ubiquitous elements of the bank-top ecosystem, these mats are not continuous. The ubiquitous occurrence of subtidal algal mats on the Great Bahama Bank (Newell *et al.* 1959; Purdy 1963; Bathurst 1967 & 1971) may relate to the development of hypersaline waters on the bank interior and consequent restriction of browsing, grazing and bioturbating organisms. It is likely that extensive mat development prohibits the formation of bank-top whitings ("mega- whitings"), except during periodic high-energy events (storms) which may disrupt mats over a large area. However, the occurrence of small-scale whitings suggests local disruption of subtidal mats with subsequent bottom sediment destabilization and resuspension during turbulent flow. A variety of factors may contribute to destruction of mats, including intermittent high flow-velocities and the activity of schools of bottom-feeding fish or other bioturbators such as *Callianassa sp.* and normal mortality of mat-building communities. Thus, the effectiveness of sediment stabilization by algae can be viewed as a balance between those factors which contribute to algal mat development (e.g. hypersalinity and consequent restriction of browsing organisms) and algal mat destruction (e.g. feeding activity of fish, bioturbation, periodic storms, mat life cycles). While it is not precisely known how these factors interact or contribute to the formation of whitings on the Great Bahama Bank, these factors must be considered in any analysis of the origin of whitings.

SUMMARY

The origin of whitings has perplexed generations of scientists conducting research on sedimentary carbonate environments of the Bahamas. However, an examination of the distribution of whitings on the northern Great Bahama Bank indicates a non-random pattern of occurrence related to the geographic limits of pellet-mud and mud sediment facies (Fig. 2; Purdy, 1963). Thus, whiting formation is controlled in part by the availability of non-pelleted, fine-grained sediment (mud contents range from 43% to 62% by weight in muddy, bank-interior facies but are <5% by weight in bank-marginal facies; Table 1; Purdy 1963).

Available chemical data provides indirect support for a resuspension origin of whitings. Bulk chemistry (pH, total alkalinity, PCO_2, relative aragonite saturation) of waters within the area of frequent whitings demonstrates that large scale instantaneous precipitation of calcium carbonate is an unlikely phenomenon (Broecker & Takahashi, 1966; Morse *et al.*, 1984). In addition, measured ^{14}C activity of aragonite collected in whitings consistently yields values indicative of formation prior to suspension in the whiting (i.e. whitings are composed of "old" bottom sediment; Broecker & Takahashi, 1966; Shinn *et al.*, 1989).

An evaluation of the dynamics of boundary layer turbulent- flow indicates that turbulence production is generated primarily during transient bursts (Kline *et al.* 1967; Kim *et al.*, 1971) during which instantaneous velocities may exceed mean flow by as much as 4 times (Grass 1971). For tidal flow on the Bahamas bank-top, this means that peak velocities in the range 32 - 200 cm s^{-1} are possible and will be accompanied by large magnitude variations in lift force over rough bottoms. It must be concluded from these data that resuspension of fine-grained (<8 um) bottom sediment similar in composition to that found suspended in whitings is a reasonable consequence of boundary layer bursting processes and that resuspension of bottom sediments is an unappreciated though potentially significant component in whiting generation.

Great Bahama Bank may be subdivided into environmental energy "facies", wherein energy is defined in qualitative terms as the flux of tidal-current, wind and wave energy. Whitings are persistent features only in those areas of the bank-top where energy flux is sufficiently high and carbonate-mud sufficiently abundant for their generation. On Great Bahama Bank, sufficient energy for sediment resuspension exists near bank margins, but sediments are nearly devoid of carbonate-mud. Thus, whitings are uncommon phenomena. Near Andros Island, carbonate mud accumulates in the "energy shadow" created by the island. Here, tidal-current, wind and wave flux are too low for mud resuspension and whiting generation. Only on the central bank- top is environmental energy sufficiently high and carbonate mud sufficiently plentiful for whitings to occur (Fig. 8).

Finally, the bottom-stabilizing influence of subtidal algal/cyanobacterial mats was considered. Previous studies showed that minimum flow velocities required for erosion and suspension of bottom sediments were significantly greater when mats were present (Neumann *et al.*, 1970). It is postulated that ubiquitous mat development over sediments in the pellet-mud and mud facies inhibits whiting formation, preventing occurrences of bank-top "mega-whiting". However, localized discontinuities in mats permit turbulent-flow processes to interact directly with bottom sediments, creating small-scale "resuspension-whitings" in these areas.

While the frequency and efficiency of many of the above processes on Great Bahama Bank is not presently well-known, it is clear that a complete understanding of Bahamian whitings will require an integrated, interdisciplinary view of the various chemical, physical, sedimentological and biological components of the Great Bahama Bank environment.

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