

Temporal and spatial distribution of whittings on Great Bahama Bank and a new lime mud budget

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ABSTRACT

Analysis of 69 shuttle and satellite images of the northern Bahamas taken from 1965 to 1993 allowed us to calculate the regional and temporal distribution and longevity of 888 whittings on the Great Bahama Bank. At any time, whittings cover between 35 and 200 km² in the area centered at lat 25°N and 78°50'W. The highest occurrences of whittings are in April and October, suggesting a seasonal component. Using a measured average of 10.6 mg/L suspended sediment in typical whittings, we calculated that 1.35×10^6 metric tons of lime mud are suspended every year. If the suspended carbonate is precipitated in the water column, these phenomena account for 280% of all of the Holocene accumulated bank top mud and more than 40% of the total bank top mud and periplatform mud that have accumulated on the west side of Great Bahama Bank.

INTRODUCTION

Photographs taken from low Earth orbit provide a unique opportunity to document spatial and seasonal components of the Earth's surface features (Andreae, 1993), including the highly debated drifting patches of lime mud found in subtropical seawater, called whittings (Tao, 1994). The phenomena have fascinated scientists for at least 30 years, and data have been provided mainly through field-based studies (Cloud, 1962; Broecker and Takahashi, 1966; Morse et al., 1984; Shinn et al., 1989; Robbins and Blackwelder, 1992; Robbins et al., 1996).

The use of photographs from space provides a distinctive approach in determining the location and transport of suspended lime mud on Great Bahama Bank. These data can then be used to calculate a sediment budget of this "carbonate machine." Estimating the production of neritic carbonates today and for the past is important in understanding the role of carbonates within the oceanic and atmospheric carbon reservoirs (Milliman and Droxler, 1995).

We believe that a significant fraction of the carbonate mud in whittings is precipitated within the water column in association with cyanobacteria based on (1) calcite and aragonite crystal size, shape, and geochemistry (Loreau, 1982; Milliman et al., 1993); (2) the intimate association of carbonate crystals and cyanobacteria cells; (3) cell counts along transects of whittings, where concentrations of planktonic cyanobacteria are double and as much as 10 times higher inside than outside whittings (Robbins et al., 1996; Thompson et al., 1997); and (4) the amino acid content of the organic fraction of the whittings (Robbins and Blackwelder, 1992). The origin of whittings and lime mud remains controversial (Broecker and Takahashi, 1966; Morse et al.,

1984; Shinn et al., 1989; Robbins and Blackwelder, 1992; Boss and Neumann, 1993) and it is not our intent to present new evidence here (see instead Yates and Robbins, 1995; Yates, 1996; Robbins et al., 1996; and Thompson et al., 1997). Field and laboratory experiments (Robbins et al., 1996; Yates, 1996) have documented that certain whittings on Great Bahama Bank originate through epicellular precipitation of calcium carbonate induced by photosynthesis in blooms of picoplankton (Robbins and Blackwelder, 1992;

Yates and Robbins, 1995; Robbins et al., 1996) or unicellular green algae (Yates, 1996).

If a significant fraction of the carbonate sediment within whittings is precipitated within the water column during a whitening event (and the references cited above suggest that to be the case), then the size and frequency distribution of whittings provides a measure of carbonate mud production. We analyzed photographs of the northern Bahamas taken by NASA astronauts from low Earth orbit to determine areal coverage of whittings and to calculate the amount of mud produced. Some aerial surveying work was undertaken to document the distribution of whittings on Great Bahama Bank (F. Morris in Morse et al., 1984; Shinn et al., 1989; Boss and Neumann, 1993), although no systematic survey of the geographical extent, seasonality of whittings, size, and temporal magnitude had been determined until now. These recent data provide a means for calculating a lime mud budget model as well as documenting a seasonal component of these phenomena.



Figure 1. Low-orbit photograph of Andros Island, Bahama (top is north), showing group of whittings to the northwest in upside-down V shape. These whittings were tracked for at least seven days and were still discrete entities on last day of documentation. Group of whittings can also be seen to south.

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METHODS

Whitings on Great Bahama Bank are easily observed from low Earth orbit (Fig. 1). A total of 888 individual whittings on Great Bahama Bank acquired from photographs were selected, mapped, and registered (Tao, 1994). The photographs were taken from the NASA manned spacecraft program (1965–1993) and catalogued by the NASA Space Shuttle Earth Observation Project. The Space Shuttle Earth observations photograph data base can be accessed on the World Wide Web at <http://ersaf.jsc.nasa.gov>. Interpretation of the selected images was based on a priori knowledge of Bahama Bank geography. Photographs were rectified and registered to 1:1 000 000 scale Operational Navigation Charts using a Bausch and Lomb zoom transfer scope. The whittings size and location were then computed and recorded and a frequency index was determined using the following equation:

$$\text{frequency index} = \frac{\text{sum of whittings area/month}}{\text{mission days}}$$

where mission days are the total number of days in orbit for each month from the data set considered. The frequency index allowed normalization of the data to eliminate bias introduced by the uneven distribution of the mission days (Andreae, 1993; Tao, 1994). These values represent the monthly variation of whittings. An additional test to verify the validity of the normalized data was performed by randomly choosing two photographs from each month and calculating the whiting frequency index, represented by the sum of the whiting size from these two photographs (Tao, 1994). Another potential bias, that 85% of the photographs only partially covered the study area (the 3300 km² of Great Bahama Bank), was addressed by selecting 10 whole bank coverage photographs and calculating the average daily whittings area. The calculated averages were consistent with observations covering the entire bank.

For lime-mud budget calculations, we show that the amount of mud found on the periplatform can be easily produced by whittings. The average water column depth used was 5 m, and the specific gravity of wet aragonite mud was $1.150 \times 10^6 \text{ g/m}^3$. We used 10.6 g/m^3 as the average whittings concentration (Shinn et al., 1989), corroborating our own field data. Our mass-balance model follows the equation:

$$\text{mass}_{\text{banktop storage}} = \text{mass}_{\text{influx}} - \text{mass}_{\text{outflux}}$$

Furthermore, we used the thickness of mud within the periplatform embayment to provide information about the amount of off-bank transported mud. According to Wilber et al. (1990), the upper slope highstand wedge is 200 km long and 7 km wide, and the average sediment thickness is 15 m. Mud composes 90% of the sediment (Wilber et al., 1990; Glaser and Droxler, 1991). On the basis of Sr concentrations, Milliman et al. (1993) suggested that 75% of the mud

fraction on the bank was produced by inorganic precipitation. We used this number (75%) in our calculations.

RESULTS AND DISCUSSION

Whittings Spatial Distribution

Figure 2 is a map of spatial distributions of whittings documented during 1965–1993. The whittings distribution showed a clear nonrandom pattern, and a large concentration around lat 25°N and 78°50'W, where 75%–85% of the whittings occurred. Smaller, more geographically dispersed whittings were also often found in the southern central part of the bank. Earlier studies (Morse et al., 1984; Shinn et al., 1989; Boss and Neumann, 1993) noted similar distributions of whittings for shorter time frames, concentrating primarily over the northern part of the bank; our comprehensive data set takes this one step further and rigorously defines the whiting occurrence on the entire bank over a 28 yr period. Although some occurrences of whittings were within the oolitic zone, most whittings occurred within the mud facies in the central part of the bank and the pellet-mud facies in the east-central part of the bank (Fig. 2).

Seasonal Variation

Whittings were observed over the entire calendar year on Great Bahama Bank, but April and October show highest frequency index values of 75 and 72 km²/day, respectively (Fig. 3). In con-

trast, the lower frequency index values occur in January, March, May, June, July, August, and September, with about 30 km² of whittings per day. Our temporal data suggest that during the 28 yr period studied, there were more whittings during the month of April and during the fall and winter months of October, November, and December than at other times of the year. Spring and fall high production months also have been observed in lake whittings where seasonal blooms of cyanobacteria have been cited (Strong and Eadie, 1978; Thompson and Ferris, 1990). Although the resuspension of bottom sediment occurs more frequently in the winter, the January through March (excluding February, for which there were no data) frequency index values were the lowest. Furthermore, whiting features analyzed had morphologically discrete shapes and distinct edges as compared with widespread resuspension events caused by stormy weather, which often showed as large bank suspensions with indistinct edges.

Time Series Whittings Observations

Shinn et al. (1989) documented the longevity of a single whiting for at least 48 hours. This type of observation was also documented by space shuttle photographs, which showed that some whittings existed for days to weeks and did not settle out in the time frame expected if they were simply stirred up bottom sediment (Tao, 1994). For example, a distinct group of whittings per-

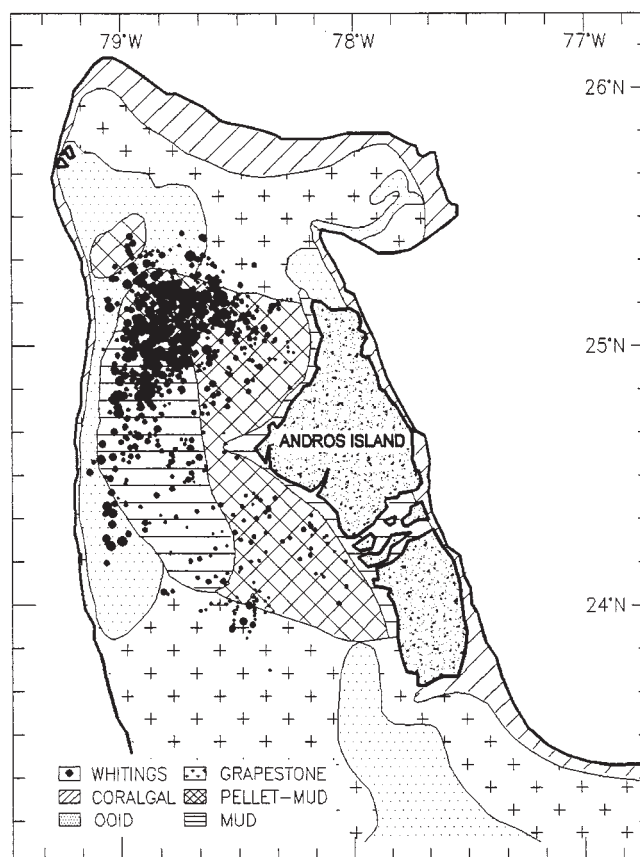


Figure 2. Spatial distribution of 888 whittings mapped from 69 NASA photographs. Whittings (black circles) demonstrate dense distribution in northwestern part of bank around lat 25°N, 78°50'W. Whittings distribution map is superimposed on sediment facies map of Great Bahama Bank (from Purdy, 1963).

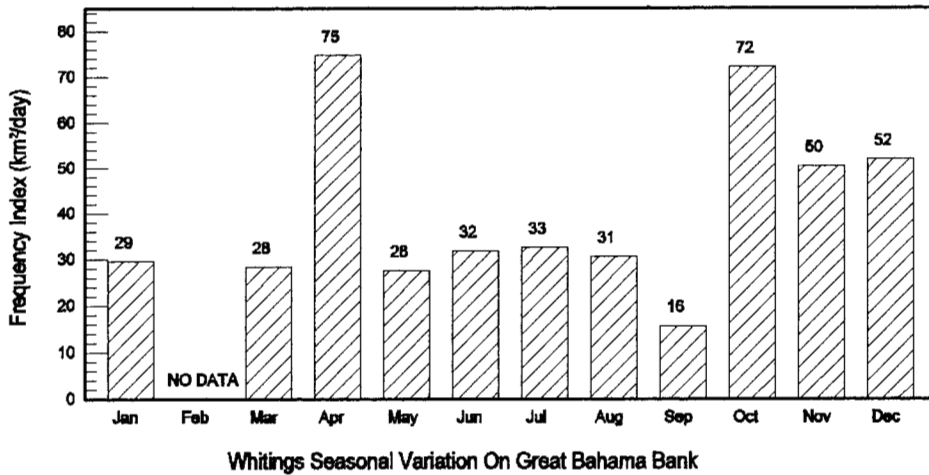


Figure 3. Seasonal variation of whittings on Great Bahama Bank. Frequency index used was monthly whittings area normalized to mission day.

sisted for at least seven days during “non-storm” conditions (Fig. 1), and of these, photographs document the evolution of a group of small whittings to larger stages. Although the group of whittings changed location and size, shape and spatial arrangement remained unchanged. Whereas this event is one of the longest duration documented in our data set, and the whittings were still prevalent on the last day photographed (October 29, 1992), a March 1994 shuttle flight (STS-62) recorded an 11 day whiting event, where individual whittings were still discrete and distinct on the last day of the flight.

LIME MUD BUDGET OF GREAT BAHAMA BANK

Serial Space Shuttle photography of the Bahamas provides a unique regional insight into the budget of lime mud. Our model mud budget (see Appendix) considers mud produced by whittings and by codiacean green algae (Neumann and Land, 1975) as major sources of fine-grained CaCO_3 . Mass outflux is off-bank transport (Neumann and Land, 1975; Wilber et al., 1990), and mass storage is the volume of lime mud on the bank top within the area of the mud and pellet mud facies (as calculated from Purdy, 1963). Mud thicknesses in the periplatform depocenter along the western margin of the bank indicate an asymmetric progradation of the lower slope depocenter (Fig. 4; Wilber et al., 1990). The maximum progradation is in the middle of the profile at about lat 25°N, having the same latitudinal range as the area of maximum whiting distribution (Fig. 4). Whereas the distribution of whittings appears to be related to the area of greatest mud progradation along the periplatform mud belt, greater thickness and width may be more related to platform margin geometry and bank-top current velocities than to source. However, the textural data, strontium content, mineralogy, and high sedimentation rate of the mud in the entire

belt strongly suggests that the mud was transported from the bank top (Wilber et al., 1990; Glaser and Droxler, 1991).

Pending further work on the detailed stratigraphy of off-bank deposits and on the regional climate of Bahama Bank over the past 6000 yr, we can only make a few simplistic assumptions. As a first approximation, we assume that the present rate of mud production is similar to the rate for the last 6000 yr (the earliest time of flooding of the bank with 2–3 m of water), although variation in

rates of transport occurred (Hine, 1983). Using our minimum, average, and maximum estimates of 35, 70, and 200 km² daily whittings area, we calculated that whittings could produce a maximum of 0.35×10^{10} m³, 0.71×10^{10} m³, and 2.0×10^{10} m³ of mud, respectively, of late Holocene deposition on the Great Bahama Bank (see Appendix). Using the geochemical constraints of Milliman et al. (1993), aragonite produced by whiting precipitation could account for ~75% of the lime mud for a two-element system. The total lime mud both on and off Great Bahama Bank (i.e., periplatform) is 1.65×10^{10} m³, as calculated from isopach maps of Purdy (1963) and Wilber et al. (1990). Wilber et al. (1990) estimated the lime-mud fraction of the mud facies of the periplatform to be about 20%–40%. The total bank-top lime-mud volume is 0.34×10^{10} m³ and the total volume of whittings-produced lime mud on the bank top at present is about 0.25×10^{10} m³, if whittings-produced aragonite accounts for 75% of the total.

Whiting Production of Lime Mud

Comparing whittings mud production and late Holocene mud deposited as bank-top sediments (0.25×10^{10} m³), even the lowest whittings production rate produces a larger volume of lime mud than is currently observed on the bank top. Thus, over the Holocene, whittings have produced more mud than is on the bank top by 40%, 180%, and 700%, using the respective whittings areas of 35, 70, and 200 km² per day. A maximum esti-

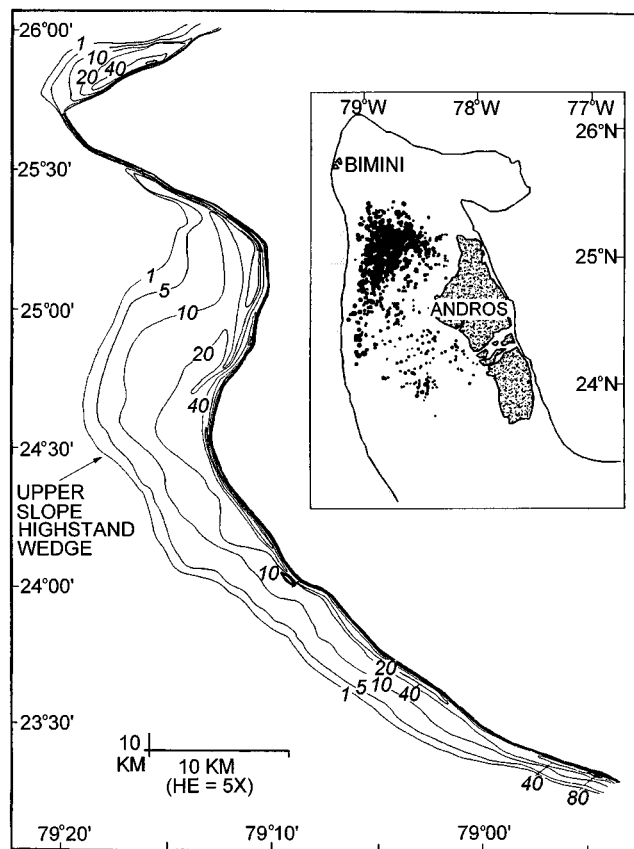


Figure 4. Isopach map of Holocene upper slope highstand wedge sediment thickness along western Great Bahama Bank. Isopleths in meters. Figure is longitudinally exaggerated five times (from Wilber et al., 1990).

TABLE A1. LIME MUD BUDGET MODEL OF GREAT BAHAMA BANK (GBB)

I. Lime mud produced by whittings:				
Average water depth (m)	5			
Area of the general GBB (m ²)	3.3 × 10 ⁹			
Average [CaCO ₃] in whiting (g/m ³)*	10.6 ± 4.5			
Density of lime mud (g/m ³) ¹	1.15 × 10 ⁶			
A. Yearly lime mud production over GBB				
	Daily whiting area (m ²)	Yearly whiting volume (m ³ /yr)	Yearly whiting mass (g/yr)	Yearly production (g/yr/m ²)
Lower limit	3.5 × 10 ⁷	6.4 × 10 ¹⁰	6.8 × 10 ¹¹	205
Average	7.0 × 10 ⁷	1.3 × 10 ¹¹	1.4 × 10 ¹²	410
Upper limit	2.0 × 10 ⁸	3.7 × 10 ¹¹	3.9 × 10 ¹²	1172
B. Mud production in 6000 yr (m³)				
	Daily whiting area (m ²)	Yearly whiting mass (m ³ /yr)	Whiting mass 6000 yr (g)	Lime-mud volume (m ³)
Lower limit	3.5 × 10 ⁷	6.8 × 10 ¹¹	4.1 × 10 ¹⁵	0.35 × 10 ¹⁰
Average	7.0 × 10 ⁷	1.4 × 10 ¹²	8.1 × 10 ¹⁵	0.71 × 10 ¹⁰
Upper limit	2.0 × 10 ⁸	3.9 × 10 ¹²	2.3 × 10 ¹⁶	2.00 × 10 ¹⁰
II. Lime mud on bank top				
Total sediment volume (m ³) [§]	1.6 × 10 ¹⁰			
Mud fraction of the total sediment [#]	20%			
Percent produced by whittings**	75%			
Mud produced by whittings (m ³)	2.5 × 10 ⁹			
III. Mud transported off-bank				
Lower depocenter mud volume (m ³) [#]	1.9 × 10 ¹⁰			
Portion produced by whittings**	75%			
Mud produced by whittings (m ³)	1.4 × 10 ¹⁰			

*Shinn et al. (1989).
¹Neumann and Land (1975).
[§]Cloud (1962).
[#]Wilber et al. (1990).
**Milliman et al. (1993).

mate using a daily whiting area of 200 km², 2.0 × 10¹⁰ m³ of lime mud would be produced by whittings. When the 0.25 × 10¹⁰ m³ of mud on the bank top is subtracted, the remaining 1.75 × 10¹⁰ m³ of lime-mud volume is large enough to accommodate both the off-bank periplatform mud (1.4 × 10¹⁰ m³) and any mud selectively dissolved in seawater and in pore waters after deposition (Droxler et al., 1988; Walter and Burton, 1990). Considering a more conservative whittings area of 70 km² / day (our average value), 0.71 × 10¹⁰ m³ of lime mud has been produced by whittings in the past 6000 yr. Although the amount of mud cannot account for both periplatform mud and bank-top mud, 0.71 × 10¹⁰ m³ of mud production in the Holocene is significant and accounts for more than 40% of the total lime-mud volume. Averaged over the study area (3300 km²), the whiting production rate is ~410 g/m²/yr, a rate comparable to previous estimates of 300–500 g/m²/yr (Broecker and Takahashi, 1966; Milliman et al., 1993).

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APPENDIX

See Table A1.

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