PROCEEDINGS OF THE 11TH SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

Edited by
Ronald D. Lewis and Bruce C. Panuska

Production Editor:
Ronald D. Lewis

Gerace Research Center
San Salvador, Bahamas
2004

Front Cover: Close-up view of a patch-reef coral head in Grahams Harbor, north of Dump Reef. As shown here, Caribbean shallow-water reefs have declined since the mid-1980s and are now largely overgrown by fleshy green macroalgae and a variety of encrusting organisms. See Curran et al., "Shallow-water reefs in transition," this volume, p. 13. Photograph by Ron Lewis.

Back Cover: Dr. A. Conrad Neumann, University of North Carolina, Chapel Hill, NC, Keynote Speaker for the 11th Symposium and author of "Cement loading: A carbonate retrospective," this volume, p. xii. Photograph by Mark Boardman.

Copycat Production Center, Auburn University, Auburn, AL.

ISBN 0-935909-72-9

AVIAN ORIGIN OF QUARTZ GRAINS IN ORGANIC-RICH SEDIMENTS FROM LOVER'S LAKE AND WARWICK POND, BERMUDA

Bruce F. Rueger
Department of Geology
Colby College
Waterville, ME 04901-8858
bfrueger@colby.edu

ABSTRACT

Organic-rich Holocene sediments from Lover's Lake and Warwick Pond, Bermuda, contain abundant amounts of sand-sized carbonate and noncarbonate mineral grains. Carbonate grains are derived from the local bedrock and/or beaches. Noncarbonate mineral grains are composed of spinel, chromite, sphene, schorlomite, perovskite, grossularite, anatase, and quartz. These grains are characteristic of the older tholeiitic igneous flows of the pedestal and are similar to those found in the Upper Member of the Town Hill Formation at Whalebone Bay. Higher concentrations of noncarbonate, nonquartz grains observed in Lover's Lake are attributable to the proximity of Lover's Lake to the outcrop at Whalebone Bay, which is being actively eroded.

The occurrence of quartz in lake sediments on Bermuda is enigmatic. Analysis of the pedestal rocks indicates that quartz did not form during the volcanic processes that led to the formation of the island. Rounded quartz grains argue against authigenic (pedogenic) origins within the soils of Bermuda. Consequently, a long-distance transport mechanism is necessary to bring the quartz grains to Bermuda.

Eolian quartz grains have been transported to Bermuda, but these are reported to be <10 μm in diameter. Thus, a mechanism other than wind is required to account for the 0.25 to 1.0 mm quartz grains extracted from the deposits of Lover's Lake and Warwick Pond. As hurricanes reaching Bermuda generally track over water and other carbonate islands, this possible source is also unlikely. The grain size of the quartz encountered is too large to be carried by normal atmospheric winds over long distances. Floating seaweed is another possibility, but seaweed arriving at Bermuda carries no known mineral matter besides carbonate. Anthropogenic influence has been a factor in historic time only. Thus, migratory birds are the most likely vector for transport of pre-anthropogenic quartz grains to Bermuda. The analysis of the contents of the digestive systems of such birds supports this hypothesis. Calculations of quartz flux using the observed abundances of quartz grains in lake sediments and bird digestive systems indicate that it would not require unrealistic numbers of birds to pass through Bermuda on an annual basis to bring the necessary amounts of quartz sand to the island.

INTRODUCTION

The occurrence of quartz grains within the organic sediments of Bermudian lake basins is enigmatic. The geology of Bermuda is comprised of carbonate eolianites capping a basaltic volcanic seamount. Volcanic conditions active in the formation of the rocks on Bermuda were silica-deficient and the presence of quartz grains implies that the grains are of allochthonous origin and arrived on Bermuda through some mechanism of long-distance transport.

Located approximately 1000 km east of North Carolina in the western Atlantic Ocean (Figure 1), the underlying volcanic pedestal of Bermuda was formed during two eruptive events. The first produced tholeiitic submarine lava flows at 90-110 myBP and the second generated titanium-rich lamprophyric intrusives forming approximately 33 myBP (Aumento and Sullivan, 1974). The mineralogic composition of the older tholeiitic submarine flows is principally andesine-labradorite laths set in a variolitic, hypocrystalline, or pilotaxic matrix, while the younger

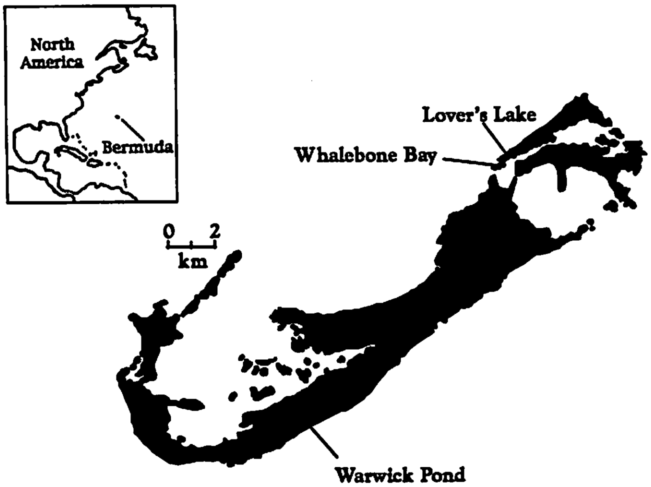

Figure 1. Map of Bermuda archipelago illustrating the locations of the Whalebone Bay, Lover's Lake, and Warwick Pond sites.

lamprophyric intrusives are composed of porphyritic sheets in which phenocrysts of olivine, clinopyroxene and biotite have been replaced by calcite pseudo-morphs, in a highly altered matrix of plagioclase and devitrified chloritic glass (Aumento and Sullivan, 1974). Both of these units were formed from low-silica magmas and consequently should not contain any quartz (Young, 1939). The volcanic units currently occur at an average depth of 75 m below sea level, but are found at a depth of only 30 m below sea level at the eastern end of the Bermuda pedestal (Rowe, 1998).

Capping the Bermuda volcanic pedestal and constituting nearly 100% of the aerially exposed bedrock on Bermuda is a sequence of five lithostratigraphic units composed of eolian calcarenites and beach deposits which accumulated during the Pleistocene (Vacher *et al.*, 1995). By use of amino acid racemization (AAR), relative ages have been determined for these units and they are thought to correspond to marine oxygen isotope stages 5a-c, 5e, 7, 9, and 11 (Vacher *et al.*, 1995).

The calcarenite units are separated intermittently by two types of geosols that formed during interglacial episodes (Rowe, 1998). Rowe (1998) stated that "white" geosols are accretionary, principally composed of limestone much like the bedrock, while "red" geosols are residual and composed of insoluble residue from the underlying limestone, organic material from plants and atmospheric dust.

Study of these soils has been somewhat enigmatic since they contain minerals, principally quartz, not indigenous to Bermuda. Sayles (1931) was the first to note the occurrence of quartz grains within the "red" geosols of Bermuda. In that investigation, Sayles (1931) observed that the grains range from clay to sand size and many are rounded, implying a source external to Bermuda. Sand-size quartz grains are also known from core samples taken from the ocean floor southeast of the Bermuda seamount (Young, 1939), and they too require an external transport mechanism. Sayles (1931) speculated on several possible transport mechanisms for the quartz grains including (1) birds, because many migratory birds are known to stop on Bermuda during migration from northern and eastern North America to Central and South America, (2) tropical hurricanes, and (3) floating gelatinous organic material and seaweed. In addition, Foreman (1951) suggested that the quartz grains might have developed during the laterization process in the formation of the soil horizons. This process, however, produces euhedral quartz grains, generally of the doubly terminated variety, which have not been observed on Bermuda.

Bricker and Prospero (1969) recognized that atmospheric dust of sizes less than 10 μm arriving on Barbados and Bermuda was principally quartz in composition and could be attributed to major dust outbreaks in the Sahara Desert region of North Africa. Blackburn and Taylor (1970) and Bricker and Mackenzie (1970) also commented on the occurrence of quartz grains in the geosols, with the former arguing against an atmospheric source of the quartz while the latter argued in favor. Additional studies by Herwitz and Muhs (1995) and Herwitz *et al.* (1996) confirmed the atmospheric origin of at least the clay and silt-size quartz grains in the geosols.

The only known exposure of material derived from the underlying volcanic pedestal is exposed in an outcrop of beach deposit within the Town Hill Formation at Whalebone Bay (Figures 1, 2a, and 2b). A relative age of 300-350 kyBP has been determined for the Town Hill Formation by use of amino acid racemization (AAR) and is

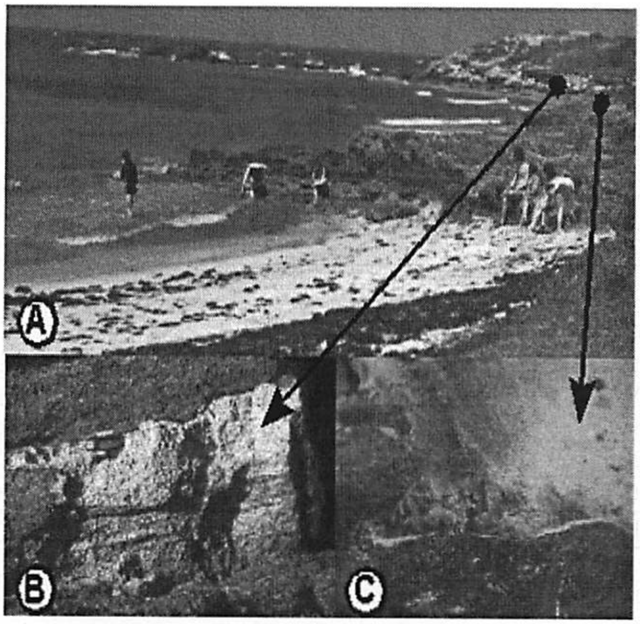

Figure 2a. View of Whalebone Bay
Figure 2b. Outcrop of heavy mineral placer sand at Whalebone Bay
Figure 2c. Heavy mineral placer sands accumulating in modern beach sands.

thought to correspond to oxygen isotope stage 9 (Vacher *et al.*, 1995). This outcrop is currently being eroded and the heavy mineral grains are being incorporated in modern beach sediments (Figure 2c).Blackburn and Taylor (1969) performed a mineralogical analysis of the black sand layers at Whalebone Bay and provided a list of minerals encountered which included apatite, chromite, garnet, gold, goethite, perovskite, anatase, and sphene. Rueger *et al.* (1996) were the first to recognize the occurrence of minor amounts of sand-size quartz in these heavy mineral beach placer deposits. Rueger (1997) reported the occurrence of sand-size quartz in the organic-rich sediments of Lover's Lake (Figure 1). Subsequently, sand-sized quartz grains have been recovered from the organic-dominated sediments from Warwick Pond (Figure 1) as well. Based on the analysis of carbonate and noncarbonate mineral grains recovered from two lake sediment cores and stomach contents of birds found on Bermuda, this investigation provides evidence implicating migratory birds as the major transport mechanism for this enigmatic quartz.

SITE DESCRIPTIONS

Lover's Lake is a small anchialine (Por, 1985) pond located in Ferry Reach Park at the southwestern end of St. George's Island, Bermuda (Figure 1). Lover's Lake developed by dissolution of the limestone within the underlying Upper Member of the Town Hill Formation by fresh water (Thomas *et al.*, 1991). Thomas *et al.* (1991) stated that angular blocks of fragmented rock exist around the margin of the lake, and steeply sloping sides encircle the basin. The average water depth of Lover's Lake is 91 cm with a maximum depth of 441 cm (Thomas *et al.*, 1991); the total pond area is 0.47 ha. Lover's Lake is connected to the ocean by a subterranean cavern system and as a result the lake has a normal marine salinity (Thomas *et al.*, 1991). Extensive organic deposits composed of mangrove peat with zones of gastropod and foraminifera remains cover the bottom of the basin. Most of the margin of Lover's Lake is presently surrounded by *Avicennia germinans* (black mangrove) thickets (Thomas and Logan, 1992). Lover's Lake serves as a significant wetland site for native and migratory birds.

Warwick Pond is situated in the south-central part of Bermuda (Figure 1). Unlike Lover's Lake, the water in Warwick Pond is fresh to brackish (Thomas and Logan, 1992); Warwick Pond covers an area of 1.66 ha (Thomas and Logan, 1992) and is also frequented by migratory and local bird populations. Warwick Pond is located in an interdune lowland that intersects the eastern part of the Warwick freshwater lens; connection between Warwick Pond and the ocean is minimal (Vacher, 1974).

METHODS

From Lover's Lake, in water 160 cm deep, a continuous core 97 cm in length was recovered using a Livingstone piston-coring device from a floating platform in June, 1996. The core was subsampled at 5 cm intervals and volume was determined for each subsample (Table 1). Samples were processed for grain-size analyses of carbonate and noncarbonate grains. The samples were processed following USGS Technical Procedure

Depth (cm)	Volume of Sample (ml)	Quartz Grains	Noncarbonate Grains	Total Grains	Quartz Grains/ml	Noncarbonate Grains/ml	Total Grains/ml
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-5	5.0	39.0	122.0	161.0	7.8	24.4	32.2
-10	9.1	4.0	8.0	12.0	0.4	0.9	1.3
-15	7.4	22.0	28.0	50.0	3.0	3.8	6.8
-20	9.4	14.0	18.0	32.0	1.5	1.9	3.4
-25	9.2	15.0	32.0	47.0	1.6	3.5	5.1
-30	7.5	19.0	25.0	44.0	2.5	3.3	5.9
-35	11.5	12.0	18.0	30.0	1.0	1.6	2.6
-40	6.6	2.0	2.0	4.0	0.3	0.3	0.6
-45	7.5	0.0	0.0	0.0	0.0	0.0	0.0
-50	6.5	2.0	10.0	12.0	0.3	1.5	1.8
-55	9.5	0.0	1.0	1.0	0.0	0.1	0.1
-60	4.5	0.0	4.0	4.0	0.0	0.9	0.9
-65	7.0	6.0	14.0	20.0	0.9	2.0	2.9
-70	10.0	29.0	178.0	207.0	2.9	17.8	20.7
-75	7.0	1.0	5.0	6.0	0.1	0.7	0.9
-80	8.7	28.0	212.0	240.0	3.2	24.4	27.6
-85	7.0	10.0	99.0	109.0	1.4	14.1	15.6
-90	9.7	16.0	120.0	136.0	1.6	12.4	14.0
			Average		1.5	6.0	7.5

Table 1. Volume, number, and concentration of noncarbonate mineral grains extracted from Lover's Lake, Bermuda for each subsample.

HP-78, R1, Nonmarine Calcareous Microfossil Preparation and Data Acquisition Procedures.

Each sample was initially treated with a hot baking soda solution. When cooled, a solution of sodium hexametaphosphate was added to allow dispersal of the sediments. The solution was allowed to stand overnight and was then frozen. Each sample was allowed to thaw and again stand overnight. Each sample was then washed through a 0.0625 mm (4.0 ϕ) screen to eliminate silt and clay-sized particles. Because the samples were dominated by organic material, they were freeze-dried to prevent clumping. Following freeze-drying, samples were dry-sieved using 1.0, 0.50, 0.25 and 0.125 mm (0.0, 1.0, 2.0, and 3.0 ϕ) sieves. All noncarbonate sand grains > 0.125 mm (>3.0 ϕ) were picked from each sample interval for this investigation. Concentrations of total noncarbonate grains/ml and quartz grains/ml in each sample were determined (Table 1) and plotted in Figure 3. -

AMS bulk radiocarbon dates of 1,570 ± 50 yBP (AA-20832), 2,155 ± 50 (AA-28033), and 3,805 ± 50 yBP (AA-23151) were obtained at depths of 33, 66 and 78 cm, respectively (Figure 3).

From a core taken at the margins of Warwick Pond in August, 1993, samples were taken at 10 cm intervals to a basal depth of 244 cm. These samples were processed following the same procedure as those taken from Lover's Lake. Concentrations of total noncarbonate grains/ml and quartz grains/ml in each sample were determined (Table 2) and plotted in Figure 4.

AMS bulk radiocarbon dates of 945 ± 55 yBP (AA-28028), 2,460 ± 55 yBP (AA-28029), 2,645 ± 55 yBP (AA-28030), and 2,455 ± 55 yBP (AA- 19859) were obtained at depths of 38, 146, 173, and 244 cm, respectively (Figure 4). Contamination is suspected in the latter sample as it is younger than the date obtained at the 173 cm depth.

Using the ^{14}C dates obtained from the core at Lover's Lake, sediment accumulation rates could be estimated. Between depths of 66 and 78 cm, the sediment accumulation rate was 0.07 mm/yr. The interval above, from 33 to 66 cm depth, the sediment accumulation rate was 0.6 mm/yr. From the sediment-water interface in

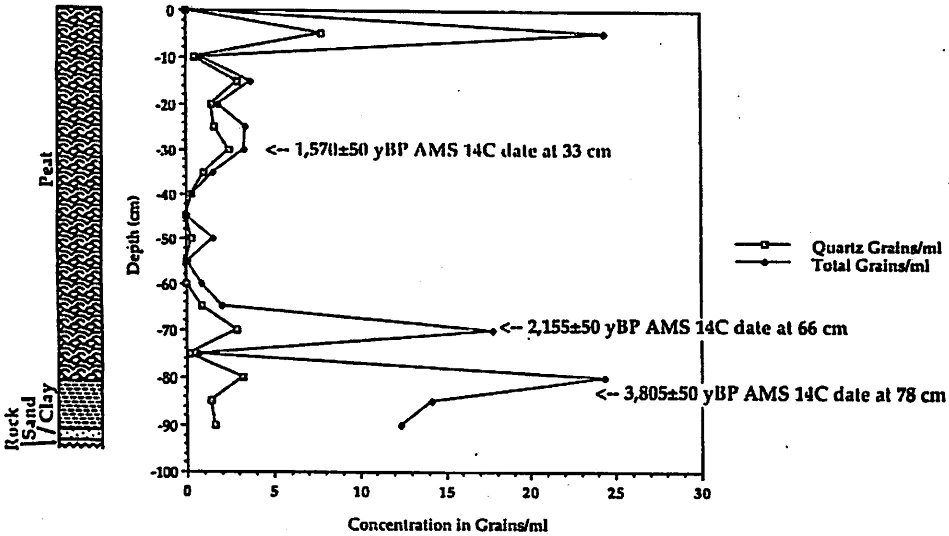

Figure 3. Distribution and concentration of total noncarbonate mineral grains and quartz grains per ml of sample analyzed in Lover's Lake sediment.

Depth (cm)	Volume of Sample (ml)	Quartz Grains	Noncarbonate Grains	Total Grains	Quartz Grains/ml	Noncarbonate Grains/ml	Total Grains/ml
0	0.25	21.0	1.0	22.0	84.00	4.00	88.00
-10	0.20	13.0	5.0	18.0	65.00	25.00	90.00
-19	0.15	9.0	0.0	9.0	60.00	0.00	60.00
-31	0.25	10.0	1.0	11.0	40.00	4.00	44.00
-41	0.50	2.0	4.0	6.0	4.00	8.00	12.00
-50	0.25	6.0	4.0	10.0	24.00	16.00	40.00
-60	1.10	10.0	4.0	14.0	9.09	3.64	12.73
-70	0.85	6.0	0.0	6.0	7.06	0.00	7.06
-80	0.65	3.0	3.0	6.0	4.62	4.62	9.23
-90	0.45	8.0	2.0	10.0	17.78	4.44	22.22
-100	0.35	4.0	2.0	6.0	11.43	5.71	17.14
-120	0.35	2.0	2.0	4.0	5.71	5.71	11.43
-130	0.90	1.0	10.0	11.0	1.11	11.11	12.22
-140	1.10	2.0	1.0	3.0	1.82	0.91	2.73
-150	2.00	4.0	8.0	12.0	2.00	4.00	6.00
-160	0.15	2.0	0.0	2.0	13.33	0.00	13.33
-170	0.25	43.0	0.0	43.0	172.00	0.00	172.00
-180	0.70	81.0	12.0	93.0	115.71	17.14	132.86
-190	0.35	62.0	9.0	71.0	177.14	25.71	202.86
-200	2.10	57.0	13.0	70.0	27.14	6.19	33.33
-210	0.60	79.0	8.0	87.0	131.67	13.33	145.00
-220	0.30	40.0	3.0	43.0	133.33	10.00	143.33
-230	1.00	21.0	1.0	22.0	21.00	1.00	22.00
-240	0.30	6.0	3.0	9.0	20.00	10.00	30.00
-244	0.10	3.0	2.0	5.0	30.00	20.00	50.00
			Average		47.2	8.02	55.18

Table 2. Volume, number, and concentration of noncarbonate mineral grains extracted from Warwick Pond, Bermuda for each subsample.

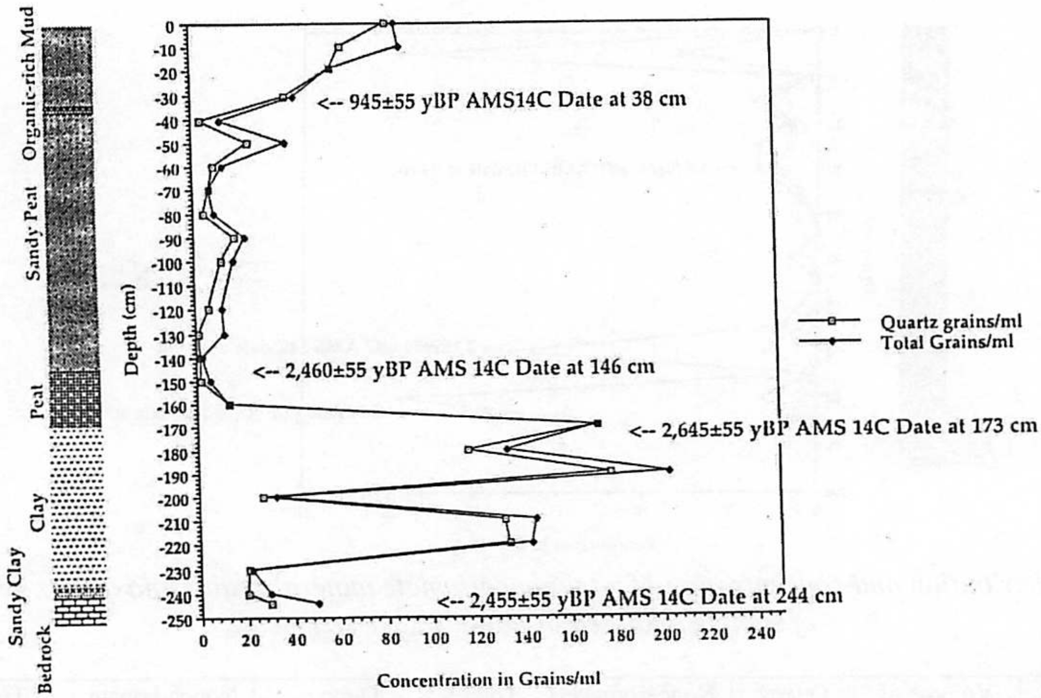

Figure 4. Distribution and concentration of total noncarbonate mineral grains and quartz grains per ml of sample analyzed in Warwick Pond

Lover's Lake to 33 cm depth, the sediment accumulation rate was 0.21 mm/yr. The average sedimentation rate for the entire Lover's Lake core was 0.2 mm/yr.

In Warwick Pond, the sediment accumulation rate between 146 and 173 cm depth was 1.5 mm/yr. Between depths of 38 and 146 cm depth, the sediment accumulation rate was 0.7 mm/yr. From the sediment-water interface to 33 cm depth, the sediment accumulation rate was 0.3 mm/yr. The average sedimentation rate for the entire Warwick Pond core was 0.7 mm/yr.

LAKE SEDIMENT RESULTS

In the core taken from Lover's Lake, three distinct sediment units were encountered (Figure 3). From the sediment-water interface to a depth of 79 cm the core was composed of a mangrove-dominated fibrous peat. From 79 to 93 cm the composition of the core was clay. The remainder of the core from 93 to 97 cm was composed of carbonate sand similar to that which forms the surrounding and underlying bedrock (Hamzi and Rueger, 1998).

Sedimentological analysis of samples from this core produced a record of highly variable concentrations of noncarbonate sand grains (Table 1). Noncarbonate sand grain concentration was highest in the clay and sand-rich materials at the base of the core and in the upper part of the core (Figure 3). Mineralogical composition of the noncarbonate sand faction was very similar to that determined of a heavy mineral placer at nearby Whalebone Bay and included spinel, chromite, sphene, schorlomite, perovskite, anatase, goethite and Fe oxides, epidote and quartz (Rueger *et al.*, 1996; Appendix 5, Rueger, 2002). In the organic sediments of Lover's Lake the minerals encountered were similar in composition and proportions, with the addition of some magnetite crystals.

The total number of all noncarbonate mineral grains encountered in individual samples of the organic sediments of Lover's Lake ranged from a minimum of 0 to a maximum of 240 grains at a depth of 80 cm (Table 1 and Figure 3). Concentrations of noncarbonate mineral grains ranged from 0.0 to 24.37 grains/ml (Figure 3); the sample containing the lowest concentration of mineral grains was 0.0 grains/ml at a depth of 45 cm (Table 1 and Figure 3). Distribution of quartz grains throughout the core mirrored the concentrations of noncarbonate grains (Figure 3). Quartz grain concentration ranged from 0.0 grains/ml at two intervals to a maximum of 7.8 grains/ml at a depth of 5 cm (Figure 3).

In the core taken from Warwick Pond five distinct lithologic units were encountered (Figure 4). From the marsh surface to a depth of 33 cm the sediment was a sandy peat with abundant gastropod shells. An organic-rich mud was present from 33 to 41 cm. Below the organic-rich mud from 41 to 146 cm the sediment encountered was a sandy peat with a large part of the sand fraction composed of carapaces from the ostracode *Cyprideis edentata* (Rueger *et al.*, 1998). A layer of peat with very little carbonate remains was encountered from 146 to 174 cm. Below the peat was a greenish-gray clay layer from 174 to 244 cm. Mud with carbonate grains and bedrock were encountered from 244 to 250 cm.

Sedimentological analysis of samples from the Warwick Pond core yielded a much higher concentration of noncarbonate sand grains (Table 2). As in the Lover's Lake core, the highest concentration of noncarbonate sand grains was found in the clay layer at the base of the core and in the sandy peat layer at the top of the core (Figure 4). Mineralogic composition of the noncarbonate sand fraction was again similar to that determined for the heavy mineral placer at Whalebone Bay and in the core from Lover's Lake. The major difference between the Warwick Pond samples and the Lover's Lake samples is the higher concentration of noncarbonate sand grains and the higher proportion of quartz sand grains in the Warwick Pond samples (Figure 4).

The total number of all noncarbonate sand grains encountered in the sediments of Warwick Pond ranged from a minimum of 2 grains at 160 cm depth to a maximum of 93 grains at 180 cm depth (Table 2 and Figure 4). Concentrations of noncarbonate mineral grains ranged from a minimum of 6.0 grains/ml at 150 cm depth to a maximum of 202.9 grains/ml at 190 cm depth (Table 2 and Figure 4). Distribution of quartz grains throughout the Warwick Pond core mirrored the concentration of total noncarbonate sand grains (Figure 4). Quartz grain concentration ranged from 1.1 grains/ml at 130 cm depth to 177.1 grains/ml at 190 cm depth (Figure 4). The range of concentration of non-quartz, noncarbonate grains in the Warwick Pond core was not significantly different than that encountered in the Lover's Lake core.

The majority of the heavy mineral fraction found at Lover's Lake and Warwick Pond represents authigenic material weathered from the younger lamprophyric intrusive of the Bermuda pedestal as indicated by the titanium-rich and silica-deficient nature of the mineral suite (Rueger *et al.*, 1996). The grains at Whalebone Bay were concentrated by continuous wave action and were deposited between 300,000 and 350,000 yBP (Vacher *et al.*, 1995). Other than the magnetite crystals from Lover's Lake, the majority of the grains at both localities are rounded, indicating considerable abrasion due to probable reworking (Appendix 5, Rueger, 2002).

ANALYSIS OF STOMACH CONTENTS

To test Sayles' (1931) suggestion that birds might be a viable transport mechanism for the sand-sized quartz grains, stomach contents of birds that died on Bermuda were analyzed for their quartz sand content. Stomach contents of 15 birds were obtained from the holdings of the Bermuda Aquarium, Museum and Zoo. Analysis of the stomach contents from these birds yielded quartz and/or rock fragments from 8 species (Table 3). These eight species included the *Arenaria interpres* (ruddy turnstone), *Capella gallinago* (common snipe), *Porzana carolina* (sora), *Gallinula chloropus* (common moorhen), *Dendrocygnus bicolor* (fulvous whistling duck), *Sialia sialis* (eastern bluebird), *Zenaida macroura* (mourning dove) and *Columbina passerina* (common ground-dove). Of these eight species, the first five are common migratory visitors to Bermuda during late summer to fall and some may winter over (Table 3). The latter three species are all residents of Bermuda and are not known to migrate

The number of quartz grains obtained ranged from a low of 7 collected from the stom-

Stomach Contents Analyzed	Quartz Grains in Stomach	Occurrence in Bermuda	Migratory Habits
Arenaria interpres (Ruddy Turnstone)	89	Resident	Common Aug. to Sept.
Capella gallinago (Common Snipe)	23	Transient	Common in October
Porzana carolina (Sora)	89	Common transient	Common Aug. to Oct., may winter
Gallinula chloropus (Common Moorhen)	43	Resident	Common Sept. to Oct., may winter
Dendrocygnus bicolor (Fulvous Whistling Duck)	23	Erratic	Rare, come from S.E. U.S.
Sialia sialis (Eastern Bluebird)	17	Resident	Some migrants
Zenaida macroura (Mourning Dove)	15	Resident	Some migrants, 99% residents
Columbina passerina (Common Ground Dove)	7	Resident	No migrants

Mean Number of Grains Encountered In Birds Analyzed	38.25
Standard Error	11.7
90 % Confidence Limit (Grains)	30.5 to 46.0
95 % Confidence Limit (Grains)	28.5 to 48.0
99 % Confidence Limit (Grains)	23.8 to 52.7

Table 3. Bird species providing stomach contents for analysis, number of quartz grains encountered, occurrence of the birds on Bermuda and migratory habits.

ach of *Columbina passerina* (common ground-dove) to a maximum of 89 grains collected from specimens of *Arenaria interpres* (ruddy turnstone) and *Porzana carolina* (sora) (Table 3). Grain sizes ranged from fine sand in the specimen of *Sialia sialis* (eastern bluebird) to pebbles and granules in the *Columbina passerina* (common ground-dove). Some of the coarser-grained material included in the stomach contents of *Zenaida macroura* (mourning dove) contained granitic material, while pebbles in *Gallinula chloropus* (common moorhen) were composed of metamorphic rocks. The majority of quartz grains extracted from these bird specimens were rounded.

In the stomach contents of the five known migratory birds analyzed, (Table 3), only the specimen of *Gallinula chloropus* (common moorhen) had any carbonate grains along with the quartz grains. Of the three known native birds, (Table 3), only *Zenaida macroura* (mourning dove) lacked a majority of carbonate grains in its stomach.

DISCUSSION

Source of the Quartz

The occurrence of quartz sand grains ranging from 0.25 to > 1.0 mm (2.0 ϕ to > 0.0 ϕ) in diameter on Bermuda is enigmatic. Since the portion of Bermuda presently above sea level is entirely limestone, and the seamount upon which Bermuda rests is composed of silica-deficient volcanic rocks which contain no quartz, an external source for the quartz is necessary, as suggested by Sayles (1931). Since human occupation of Bermuda did not begin until 1609 (Zuill, 1946; Wilkinson, 1958), the quartz in older Holocene lake sediments and the Pleistocene rocks at Whalebone Bay indicates quartz sand has been accumulating throughout pre-history without an anthropogenic influence. Due to the location and prehistoric isolation of Bermuda, the potential sources of the quartz sand are limited.

Inwash and secondary reflux to the Lover's Lake and Warwick Pond basins is also possible, but this would only have impacted the lower clay layers of the core where they would have become concentrated by erosion during the glacial maximum. Dates obtained from the core material are too young to support this hypothesis.

Wind has been determined as the transport mechanism for the dust-sized quartz particles integral in the formation of the red geosols of Bermuda (Sayles, 1931; Bricker and Prospero, 1969 and Herwitz *et al.*, 1996), but captured atmospheric aerosol particles are much smaller than the 0.25 to 1.0 mm (2.0 to 0.0 ϕ) quartz particles which form the focus of this investigation. Wind, even with sea level at a low-stand during glacial maximum, which would decrease the distance between the Atlantic Coastal Plain and Bermuda, is not a viable source of quartz of this size. Wind arriving at Bermuda in the summer and fall are primarily from the southwest and those arriving in the winter and spring are largely from the west. Velocities associated with these winds are capable of transporting particles in the range of 10 to 50 μm (0.010 to 0.050 mm) (Rueger, 2002).

The only other atmospheric process capable of higher wind velocity affecting Bermuda would be hurricanes. Hurricanes have been relatively infrequent visitors to Bermuda during historical time with frequency ranging from 0 to 6 hurricanes per decade since 1609, with an average of approximately 1-3 per decade (Tucker, 1995).

To further explore the possibility of hurricanes bringing sand grains to Bermuda by long-distance transport, records of tropical storms and hurricanes were considered. Only those affecting the western Atlantic Ocean, the Caribbean Sea, the Gulf of Mexico and the east coast of North America, passing in close proximity to Bermuda were included in the analysis. Between September, 1852, and September, 2000, a total of 254 storms received status of tropical storm or hurricane and passed near Bermuda (Rueger, 2002). On average, 1.7 storms/year affected the region.

Of these storms, 83, or 33% of the storms actually made landfall on Bermuda or anywhere else including the southeastern United States and the Caribbean region (Rueger, 2002). Of the 83 storms that did make landfall, 39, or 45% of those storms made landfall on continental areas or islands that were not composed principally of carbonate bedrock.

Only 17 hurricanes of the 254 storms passed close enough to actually strike Bermuda during the interval between September, 1852 and September, 2000 (Rueger, 2002). Of the 17 hurricanes that struck Bermuda, 7, or 41% made landfall prior to reaching Bermuda. Only 5 hurricanes, or 2% of all the storms passing in proximity to or striking Bermuda actually made landfall on non-carbonate based terrestrial landmasses prior to arriving at Bermuda.

While storms of this magnitude and nature may have the capability of carrying some clastic or quartz sand grains to Bermuda, the low frequency at which they arrive is not likely to result in a significant contribution to island. Because most of the hurricanes reaching Bermuda track principally over water hurricanes are concluded not to be from being a major factor in transporting quartz grains to Bermuda.

Foreman (1951) considered quartz formation during the laterization of the Bermudian soil horizons as a possible local source. This phenomenon had been observed in the tropics by Harrison (1933), but due to the fact that most of the grains are rounded, it may be necessary for abrasion to take place prior to deposition on Bermuda.

Seaweed floating to Bermuda could bring quartz sand to Bermuda but transporting the quartz from beaches to Lover's Lake and Warwick Pond would complicate the viability of this mechanism. Unattached sargassum seaweed (*Sargassum natans* and *Sargassum fluitans*) commonly washes up on the beaches of Bermuda and while it has been studied and determined capable of contributing carbonate material, no quartz grains have been observed (Pestana, 1985).

Humans can be eliminated as a major source for all but the most recent material since colonization is known to have occurred in 1609.

However, the high concentrations of quartz grains in the upper section of the core (Figure 2) can attributed to anthropogenic activity since Ferry Reach Park has a long history of human use, particularly those utilizing concrete in construction. Forts have been constructed in the area and a railroad was built in the 1930-1940s. The Warwick Pond area also supports a high concentration of modern paved roads and residential and business structures. Quartz sand has been recently imported for use in sand traps on island golf courses. The specimen of *Zenaida macroura* (mourning dove) demonstrates the validity of this source of quartz, since 15 quartz sand grains (Table 2) were found in its stomach and the bird was found dead at the 4th tee of the Riddell's Bay Golf Course. This same specimen of *Zenaida macroura* (mourning dove) had granite pebbles in its stomach, which were traced to peastone imported for road construction.

Some of the increased influx of noncarbonate grains in the upper part of the Lover's Lake core may also be attributed to erosion of the placer deposit at Whalebone Bay and redeposition of some of these grains. The stomach contents of the remaining native, non-migratory birds (Table 2) contained mostly carbonate grains, indicative of local feeding habits. The majority of the grains examined in the stomach contents of these specimens are also rounded.

The above arguments leave birds as the sole viable remaining candidate as a transporting vector for the quartz sand. Birds have long used the Gulf Stream and atmospheric circulation patterns for migration. Columbus, noting a "river of birds" in the western Atlantic Ocean used this evidence of his proximity to land in his voyage to North America in 1492 (Willis, 1992). Since birds have been found with quartz grains in their stomach contents and quartz grains have been found in the organic sediments of Lover's Lake and Warwick Pond, both known migratory stopover sites, significant quantities of quartz grains have apparently been transported to Bermuda by this mechanism.

Hui and Beyer (1998) indicated that the amount of sediment ingested by an organism can vary significantly between species and larger taxonomic groups. Beyer *et al.* (1994) documented that ingestion of sediment by various organisms during feeding can occur on a large scale and in large volumes. However, this mechanism of sedimentary transport by wildlife in not well reported in the literature. The majority of studies related to sediment ingestion by organisms have been performed as biological investigations to assess and determine risks of exposure to environmental contaminants or to document sources of nutrients for animals.

Kopischke (1966) reported that *Phasianus colchicus* (pheasants) and other bird species consume soil and sediments as a source of dietary calcium and for grit to be used to aid in digestion. Reeder (1951) analyzed the volumes of sediment ingested by eight species of shorebirds and determined that 10 to 60% of the material found in the digestive tracts of these birds was composed of sand-sized mineral particles. In sandpipers, Beyer *et al.* (1994) determined that sand-sized particles represented 7 to 30% of the material within the digestive tracts of these birds. Hui and Beyer (1998) sampled small populations of *Pluvialis squatarola* (black-bellied plovers) and *Catoptrophorus semipalmatus* (willets) to determine volumes of sediment ingestion by these birds. In that investigation it was observed that 29% of the material ingested by plovers and 3% ingested by willets was sand. It was also noted that sand grains constituted 9% of the material ingested by woodcocks and 8% ingested by Canada geese.

As noted, sediment ingestion by shorebirds is widespread (Reeder, 1951; Beyer *et al.*, 1994 and Hui and Beyer, 1998). In addition, it was concluded that the volume and type of sediment ingested was closely related to diet and foraging techniques and feeding mechanisms of the individual species of birds studied (Hui and Beyer, 1998).

When sea level was lower during glacial times, many more ponds such as Lover's Lake and Warwick Pond existed on the Bermuda platform allowing quartz sand grains to accumulate there. These grains were subsequently subjected to further redistribution by wind and wave activity as sea level rose. This may account for the recovery of quartz sand grains in deep ocean sediments as reported by Young (1939) and in the geosols of Bermuda, as the clays at the base of the Lover's

Lake and Warwick Pond cores have been interpreted (Figure 3 and 4).

Quartz Flux From Birds

Since volumetric samples were used in this investigation and the modern areas of Lover's Lake and Warwick Pond are known, the number of birds required to bring the necessary quantities of quartz sand to Bermuda can be estimated. However, since it is recognized that there is an anthropogenic quartz influx to the sediments in the upper depths of the two ponds, the upper peaks in Figures 3 and 4 were not included in this calculation. The high quantities of quartz in the basal sediments of the cores also represent an accumulation bias due to the residual concentration of quartz and other noncarbonate minerals grains in this unit. Therefore, the lower peaks readily visible in the stratigraphy of the two cores were not utilized. To eliminate this complication, the quartz concentration data between depths of 10 and 60 cm in Lover's Lake and 31 and 150 cm in Warwick Pond were used (Tables 1 and 2). These data are thought to provide a more accurate index of the number of birds required for transport of quartz grains to Bermuda in these amounts.

The area of Lover's Lake is 0.47 ha and the volume of the samples between 10 and 60 cm was known, the number of birds required to bring the observed quantity of quartz sand to Lover's Lake can be estimated. With a radiocarbon date of 3805 ± 50 yBP at a depth of 78 cm in the core, an average sedimentation rate of 0.2 mm/yr can be estimated. The maximum quartz concentration in the core between depths of 10 and 60 cm was 2.97 grains/ml, while the minimum concentration was 0.3 grains/ml and the average concentration was 0.97 grains/ml (Table 4).

Using the area of the pond, the average sedimentation rate, maximum, minimum and average concentrations, and the number of quartz grains per bird, the number of birds required to bring this much quartz sand to Bermuda can be assumes the cores analyzed are representative of the basin. The mean number of grains encountered roughly determined. Of course, this calculation in the stomachs of the birds analyzed in this investigation is 38.3 grains (Table 4). Using a student t-test on the small population of birds potentially providing quartz grains to both Lover's Lake and Warwick Pond, the 95% confidence limits of this test provided a range of 28.5 to 48.0 grains per bird (Table 4). From this range of values and using the highest quartz concentration from Lover's Lake, it would require between 58,000 to 98,000 birds per year to bring this quantity of quartz sand to Bermuda (Table 4). For the lowest quartz concentration, 5900 to 9900 birds per year would be required and for the average quartz concentration 19,000 to 32,000 birds per year would be required (Table 4).

The same calculations can be made for the sediments obtained from Warwick Pond. Using the lowest presumed valid date for Warwick Pond, 2645 ± 55 yBP at a depth of 173 cm, an average sedimentation rate of 0.7 mm/yr can be estimated. The maximum quartz concentration in the interval between depths of 31 and 150 cm in the Warwick Pond core was 40 quartz grains/ml, while the minimum concentration was 1.11 quartz grains/ml, with the average being 10.92 quartz grains/ml (Tables 2 and 4).

Using the area of Warwick Pond, the average sedimentation rate, highest, lowest and average quartz grain concentrations and the range of quartz grains/bird derived from the student t-test, the number of birds required to bring this quantity of quartz sand to Bermuda can be roughly estimated as well. For the highest concentration of quartz sand found in Warwick Pond, it would require between 9,200,000 and 15,500,000 birds per year to visit Bermuda each year (Table 4). For the average concentration, 2,500,000 to 4,450,000 birds per year would be necessary, while for the lowest concentration, 256,000 to 430,000 birds per year would be required (Table 4). These calculations indicate far more birds visiting Bermuda than has been recorded over the past 50 years. The average numbers though, are within the range that would have been observed by the early colonists on the island and through the late 1800s (David B. Wingate, personal communication).

The higher numbers of birds visiting Warwick Pond and consequent higher concentrations of quartz grains in the sediment is attributed to the much larger size of Warwick Pond and the

Parameter	Lover's Lake	Warwick Pond
Area of Pond or Lake	0.47 ha	1.66 ha
Average Sedimentation Rate	0.2 mm/yr	0.7 mm/yr
Highest Quartz Concentration	2.97 grains/ml	40 grains/ml
Lowest Quartz Concentration	0.3 grains/ml	1.11 grains/ml
Average Quartz Concentration	0.97 grains/ml	10.92 grains/ml
Mean Number of Grains/Bird	38.3	38.3
95 % Confidence Limits for Mean	28.5 to 48.0	28.5 to 48.0
Number of Birds for Highest Concentration	58,000 to 98,000	9,200,000 to 15,500,000
Number of Birds for Lowest Concentration	5900 to 9900	256,000 to 430,000
Number of Birds for Average Concentration	19,000 to 32,000	2,500,000 to 4,450,000

Table 4. Number of birds required to transport quartz sand sediment to Bermuda at concentrations determined from Lover's Lake and Warwick Pond, Bermuda

fresh water contained within it, making a more suitable refuge.

Reasons for a Decline in Bird Visits

Declines in neotropical and nearctic migratory bird populations over the past 40 years in eastern North America have been reported in numerous ornithological studies (Robbins *et al.*, 1989, Askins *et al.*, 1990, Hill and Hagan, 1991, Böhning-Gaese *et al.*, 1993, Peterjohn and Sauer, 1994 and Rappole and McDonald, 1994). While there is not a consensus as to how much of a decline has occurred, if at all, several causes for this decline have been proposed.

Robbins *et al.*, (1989), Hill and Hagan (1991) and Rappole and McDonald (1994), argued that the best explanation for their observed declines in migratory bird populations is the alteration of wintering-ground habitats. With deforestation occurring at alarming rates since pre-Columbian times on a widespread scale in Belize, Costa Rica and Mexico, large regions of usable habitat has been lost in these regions (Rappole and McDonald, 1994). The same can be said of habitats on Bermuda with the arrival of colonists in 1609 and loss of forest for dwellings, agriculture and mortality due to scale insect infestation (Challinor and Wingate, 1971). Habitat has also been lost at a high rate or is being destroyed due to coastal development and wetland alteration along the coasts of North America.

Forest fragmentation in breeding regions of these migratory birds is proposed as the cause of the observed decline by Böhning-Gaese *et al.* (1993) and Peterjohn and Sauer (1994). As forest regions have been broken up through urbanization over the past 40 years, habitat for neotropical migratory birds has been diminished or lost (Askins *et al.*, 1990). This trend may have occurred in eastern North America as large areas of forest were cleared during the post-colonial era, which may not be well documented.

Several authors (Askins *et al.*, 1990, Hill and Hagan, 1991, and Böhning-Gaese *et al.*, 1993), also consider predation and parasitism of nests as a cause for migratory bird population declines. They also contend that this may be related to decreasing forest size and fragmentation in eastern North America.

Askins *et al.* (1990), in their survey of studies on migratory bird populations in eastern North America, recognized all three factors as potential causes, focusing on the anthropogenic impact on these populations. The authors argued for the preservation of forests in breeding and wintering areas and against subdivision of forests to prevent the downturn.

The observations of these authors tend to support a decline in migratory bird populations in eastern North America. No longer do the "rivers of birds" observed by Columbus in his voyages pass through the eastern skyways at that scale (Willis, 1992). On Bermuda, there has been a decrease of 50% in the numbers of birds actually arriving on Bermuda since the 1960s (David Wingate, Bermuda Conservation Officer, personal communication). Wingate indicates that the number of birds arriving on Bermuda is approximately 100,000 per year. Prior to the 20th Century, Wingate estimates that the numbers were within the range of 400,000 to 1,000,000 birds per year. Williams *et al.*, (1977) indicated that "large numbers" of birds annually fly over Bermuda on their way to southern locales. Brian Harrington (Manomet Center for Conservation Sciences, personal communication) indicated that many shorebirds routinely fly between North and South America during migration. Most of these birds currently do so by nonstop flights that originate in the northeastern US and/or Canadian Maritimes (depending on species), and make landfall on the northern coast of South America (e.g. The Guianas/Venezuela region). Radar studies show that many of these birds are passing over and in the vicinity of Bermuda heading on a southeastern bearing (Ireland and Williams, 1974, Williams *et al.*, 1977 and Stoddard *et al.*, 1983). McClintock *et al.* (1978) in studies between 14 September and 6 October, 1973, and 26 September and 22 October, 1974, observed numbers of birds per day in the vicinity of Bermuda ranging between 1 and 100 birds. Birds captured on ships were found to have sand grains in their stomach contents (McClintock *et al.*, 1978). Several shipboard reports also noted large amounts of shorebirds and passerines in the vicinity of Bermuda (Hurdis, 1897 and Scholander, 1955). Hurdis (1897) noted "great flocks of shorebirds stretching from horizon to horizon." Bradlee *et al.* (1931), in a checklist of birds on Bermuda, listed 84 species of birds as frequent visitors during migratory seasons and 138 species as occasional or accidental visitors. Relatively few of these birds stop in Bermuda today, presumably because the habitat conditions do not provide the abundant food resources that would attract them (Ireland and Williams, 1974). Wingate (1973), however, indicated that species populations of birds on Bermuda vary on an annual basis and these changes indicate that birds do land on Bermuda. Declines in migratory bird populations in eastern North America supports the observed declines in quartz-grain influx to Lover's Lake and Warwick Pond because the numbers of birds required no longer reach the islands.

CONCLUSIONS

Sedimentological and mineralogical analyses of the noncarbonate sediments from the organic sediments from Lover's Lake and Warwick Pond indicate that the material from both ponds is similar to that found in the Upper Member of the Town Hill Formation at Whalebone Bay.

Higher concentrations of noncarbonate, nonquartz grains observed in Lover's Lake are attributable to the proximity of Lover's Lake to the outcrop at Whalebone Bay, from which sediment of this nature is being actively and continually eroded.

The quartz grains are also preserved in the sediments of both lake sites. Analysis of the pedestal rocks indicates that quartz did not form during the volcanic processes that led to the formation of the island. Rounded quartz grains argue against authigenic pedogenic origins within the soils of Bermuda. Consequently, a long-distance transport mechanism is necessary to bring the quartz grains to Bermuda.

As hurricanes that reach Bermuda generally track over water and other carbonate islands, this possible source is unlikely. The grain-size of the quartz encountered in the lake basins (0.25 to 1.0 mm) is too large to be carried by normal atmospheric winds over long distances. Floating seaweed is possible, but seaweed arriving at Bermuda carries no known mineral matter besides carbonate with it. Anthropogenic influence has been a factor in historic time only. Migratory birds are thus the most likely vector for pre-anthropogenic quartz grains to Bermuda. The analysis of the contents of the digestive systems of these birds supports this hypothesis. Calculations of quartz flux using the observed abundances of quartz grains in lake sediments and bird digestive systems indicate that it would not require unrealistic numbers of birds to pass through Bermuda on an annual basis to bring the necessary amounts of quartz sand to the island.

ACKNOWLEDGMENTS

Research included in this investigation was funded by grants from the following organizations and institutions: Colby College Natural Sciences Division grant program; the Dean of the Graduate School's Small Grant Fund at the University of Colorado; the Society of Wetland Scientists; Geological Society of America Graduate Research Grants 5237-93 and 5453-94; Bermuda Zoological Society Grants and a Grant-In-Aid from the Bermuda Biological Station for Research.

Gratitude is extended to Mrs. Lisa Greene, Collections Officer, Dr. Wolfgang Sterrer, Curator, Mr. Richard Winchell, formerly Principal Curator, all of the Bermuda Aquarium, Museum and Zoo, and Dr. David Wingate, Bermuda Conservation Officer for their immeasurable assistance in the field and for logistical help on Bermuda. Dr. Brian Harrington was of great help in supplying data regarding migratory birds routes and population densities. Encouragement for this project was offered from Drs. Donald B. Allen, Robert A. Gastaldo, Robert E. Nelson, Harold R. Pestana and Edward Yeterian of Colby College.

This is contribution #71 to the Bermuda Biodiversity Project (BBP), Bermuda Aquarium, Museum and Zoo.

This is contribution #1644 of the Bermuda Biological Station for Research.

REFERENCES

Askins, R.A., Lynch, J.F., and Greenberg, R., 1990, Population declines in migratory birds in eastern North America, *in* Power, D.M., ed., Current Ornithology, v. 7, p. 1-57.

Aumento, F., and Sullivan, K.D., 1974, Deep drill investigations of the oceanic crust in the North Atlantic, *in* Kristjansson, L., ed., NATO Advanced Study Institute Series, Series C, Mathematics and Physical Sciences, vol. 11, Geodynamics of Iceland and the North Atlantic area, p. 83-103.

Beyer, W.N., Connor, E.E., and Gerould, S., 1994, Estimates of soil ingestion by wildlife: Journal of Wildlife Management, v. 58, p. 375-382.

Blackburn, G., and Taylor, R.M., 1969, Limestones and red soils of Bermuda: Geological Society of America Bulletin, v. 80, p. 1595-1598.

Blackburn, G., and Taylor, R.M., 1970, Limestones and red soils of Bermuda: Reply: Geological Society of America Bulletin, v. 81, p. 2525-2526.

Böhning-Gaese, K., Taper, M.L., and Brown, J.H., 1993, Are declines in North American insectivorous songbirds due to causes on the breeding range?: Conservation Biology, v. 7, p. 76-86.

Bradlee, T.S., Mowbray, L.L., and Eaton, W.F., 1931, A list of birds recorded from the Bermudas: Proceedings of the Boston Society of Natural History, v. 39, p. 279-382.

Bricker, O.P., and Prospero, J.M., 1969, Airborne dust on Bermuda Islands and Barbados: Eos, v. 50, p. 176.

Bricker, O.P., and Mackenzie, F.T., 1970, Limestones and red soils of Bermuda: Discussion: Geological Society of America Bulletin, v. 81. p. 2523-2524.

Challinor, D., and Wingate, D., 1971, The struggle for survival of the Bermuda cedar: Biological Conservation, v. 3, p. 220-222.

Foreman, F., 1951, Study of some Bermuda rocks: Geological Society of America Bulletin, v. 62, p. 1297-1330.

Hamzi, W.M., and Rueger, B.F., 1998, Biostratigraphy of Late Holocene sediments from Lover's Lake, Bermuda: Geological Society of America Abstracts with Programs, v. 30(7), p. A-163.

Harrison, J.B., 1933, The katamorphism of igneous rocks under humid tropical conditions. Imperial Bureau of Soil Sciences, Rothamsted Experimental Station, Harpenden, 79 p.

Herwitz, S.R., and Muhs, D.R., 1995, Bermuda solution pipe soils: A geochemical evalutation of eolian parent materials, *in* Curran, H.A., and White, B., eds., Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda, Geological Society of America Special Paper 300, p. 311-323.

Herwitz, S.R., Muhs, D.R., Prospero, J.M., Mahan S., and Vaughn, B., 1996, Origin of Bermuda's clay-rich Quaternary paleosols and their paleoclimatic significance: Journal of Geophyisical Research, v. 101, p. 23,389-23,400.

Hill, N.P., and Hagan, J.M., III, 1991, Population trends of some northeastern North American landbirds: a half-century of data: The Wilson Bulletin, v. 103, p. 165-182.

Hui, C.A., and Beyer, W.N., 1998, Sediment ingestion of two sympatric shorebird species: The Science of the Total Environment, v. 224, p. 227-233.

Hurdis, J.L., 1897, Rough notes and memoranda relating to the natural history of the Bermudas by the late J.L. Hurdis, edited by his daughter, H.J. Hurdis, R.H. Potter, London.

Ireland, L.C., and Williams, T.C., 1974, Radar observations of bird migration over Bermuda, *in* Gauthereaux, S.A., ed., Proceedings of a Conference on the Biological Aspects of the Bird/Aircraft Collision Problem, p. 383–408.

Kopischke, E.D., 1966, Selection of calcium- and magnesium-bearing grits by pheasants in Minnesota: Journal of Wildlife Management, v. 30, p. 276-279.

McClintock, C.P., Williams, T.C., and Teal, J.M., 1978, Autumnal bird migration observed from ships in the western North Atlantic Ocean: Bird Banding, v. 49, p. 262-277.

Pestana, H.R., 1985, Carbonate sediment production by *Sargassum* epibionts: Journal of Sedimentary Petrology, v. 55, p. 184-186.

Peterjohn, B.G., and Sauer, J.R., 1994, Population trends of woodland birds from the North American breeding bird survey: Wildlife Society Bulletin, v. 22, p. 155-164.

Por, F.D., 1985, Anchialine pools-comparative hydrobiology, *in* Friedman, G.M., and Krumbein, W.E., eds., Hypersaline Ecosystems, The Gavish Sabkha, Ecologicial Studies 6. Springer-Verlag, New York, p. 136-144.

Rappole, J.H., and McDonald, M.V., 1994, Cause and effect in population declines of migratory birds: The Auk, v. 111, p. 652-660.

Reeder, W.G., 1951, Stomach analysis of a group of shorebirds: The Condor, v. 53, p. 43-45.

Robbins, C.S., Sauer, J.R., Greenberg, R.S., and Droege, S., 1989, Population declines in North American birds that migrate to the neotropics: Proceedings of the National Academy of Sciences, v. 86, p. 7658-7662.

Rowe, M.P., 1998, An explanation of The Geology of Bermuda (2nd Edition). Bermuda Ministry of the Environment, Hamilton, 30 p.

Rueger, B.F., 1997, Avian origin of quartz grains in organic-rich sediments from Lover's Lake, Bermuda: Geological Society of America Abstracts with Programs, v. 29(6), p. A-65.

Rueger, B.F., 2002, Holocene Environments of Bermuda. [Doctoral Dissertation]: University of Colorado, Boulder, CO, 357 p.

Rueger, B.F., Allen, D.B., Bayles, S.H., Dreisbach, E.T., and van der Hoeven, K.J., 1998, Sedimentological, mineralogical and paleoecological analyses of Late Holocene deposits in Warwick Pond, Bermuda: Geological Society of America Abstracts with Programs, v. 30(7), p. A-163.

Rueger, B.F., Pestana, H.R., and Allen, D.B., 1996, Provenance of a heavy mineral beach sand, Whalebone Bay, Bermuda: 14th Biennial Meeting of the American Quaternary Association Program and Abstracts, p. 120.

Sayles, R.W., 1931, Bermuda during the ice age: Proceeding of the American Academy of Arts and Sciences, v. 66, p. 381-467.

Scholander, S.I., 1955, Land birds over the western North Atlantic: The Auk, v. 72, p. 225-239.

Stoddard, P.K., Marsden, J.E., and Williams, T.C., 1983, Computer simulation of autumnal bird migration over the western North Atlantic, Animal Behavior, v. 31, p. 173-180.

Thomas, M.L.H., Eakins, K.E., and Logan, A., 1991, Physical characteristics of the anchialine ponds of Bermuda: Bulletin of Marine Science, v. 48, p. 125-136.

Thomas, M.L.H. and Logan, A., 1992, A guide to the ecology of shoreline and shallow-water marine communities of Bermuda: Bermuda Biological Station for Research Special Publication 30, 346 p.

Tucker, T., 1995., Beware the Hurricane. The Island Press Ltd., Bermuda 178 p.

Vacher, H.L., 1974, Groundwater hydrology of Bermuda: Bermuda Public Works Department, Hamilton, 85p.

Vacher, H.L., Hearty, P.J., and Rowe, M.P., 1995, Stratigraphy of Bermuda: nomenclature, concepts, and status of multiple systems of classification, *in* Curran, H.A., and White, B., eds., Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda, Geological Society of America Special Paper 300, p. 271-293.

Wilkinson, H.C., 1959., The Adventurers of Bermuda, (2nd edition). Oxford University Press, London, 421 p.

Williams, T.C., Williams, J.M., Ireland, L.C., and J.M. Teal, 1977, Autumnal bird migration over the western North Atlantic Ocean: American Birds, v. 31, p. 251-267.

Willis, E.O., 1992, Columbus and the river of birds: Natural History, v. 101(10), p. 22-29.

Wingate, D.B., 1973, A checklist and guide to the birds of Bermuda. Hamiltion, Bermuda, The Island Press, Ltd.

Young, J.A., Jr., 1939, Minerals from deep sea cores and surface deposits of Bermudian calcareous sediments: American Journal of Science, v. 237, p. 798-810.

Zuill, W., 1946, Bermuda Journey, A Leisurely Guidebook. The Bermuda Book Stores, Hamilton, Bermuda, 426 p.