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Sequestration of Carbonate Shell Material in Coastal Dunes on the Gulf of California (Baja California Sur, Mexico)

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ABSTRACT

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Atmospheric and oceanographic conditions stimulate high productivity of marine organisms in the Gulf of California that are bulk producers of calcium carbonate. Due to prevailing winter winds, north-facing beaches receive vast amounts of shell debris derived from offshore clam banks above the 50-m isobath. As shells undergo mechanical abrasion, the smaller particles of carbonate material are transferred from beaches by the wind and sequestered in coastal dunes. This study reports on two dune fields from the midriff zone of the Gulf. Sieve analysis is used to describe the grain size and sorting characteristics of seven samples from dunes at Cerro El Gallo near Mulegé and 12 samples from dunes farther south near San Nicolás. Dune sediments also were impregnated with epoxy to simulate rock samples from which thin sections were made to determine composition and relative abundances of constituent grains. The dunes at Cerro El Gallo are carbonate poor (5–15%) compared with those near San Nicolás (26–51%) and possible factors contributing to regional variation are explored.

Another part of this study appraises the fecundity necessary to produce any carbonate fraction integrated by coastal dunes from seashells. One of the region's more abundant clams, *Megapitaria squalida,* was used as a model to estimate the number of individuals of a given size and age class required to generate a cubic meter of pure carbonate sand. Satellite images of the dune fields at El Gallo and San Nicolás were viewed to map surface coverage. With input on the thickness of dune deposits and their composition, it is possible to roughly estimate the number of mature *Megapitaria* equal to the carbonate fraction of these dunes. The method may be applied to all coastal dunes on the Gulf of California and could be used to assess a part of the region's overall carbon budget heretofore unappreciated.

ADDITIONAL INDEX WORDS: *Mollusk beds, Chocolata Shell (*Megapitaria squalida*), beach deflation, carbonate dunes, carbon cycle, remote sensing.*

INTRODUCTION

With its narrow shape and high surrounding topography, the Gulf of California plays host to a complex set of atmospheric and oceanic conditions. Aspects of thermohaline circulation and Ekman transport interact to promote seasonal upwelling (Alvarez-Borrego, 2002; Bray, 1988; Bray and Robles, 1991; Roden, 1964). As a result, primary biological productivity is prodigious (Alvarez-Borrego and Lara-Lara, 1991; Zeitzschel, 1969), and the region supports a diverse array of marine invertebrates that commonly secrete calcareous shells, skeletons, or tests (Brusca, 1980; Keen, 1971). Numerous localities with carbonate-sand beaches occur as pockets along the length of the peninsula's gulf coast (Carranza-Edwards *et al.,* 1998).

In addition to carbonate beaches, the gulf margin of the Baja California peninsula features coastal dune fields that incorporate significant amounts of calcium carbonate derived from seashells. Overall, dune fields cover about 5% of the Earth's surface (Thomas, 1997). A subset of these dunes consists of carbonate eolianites that form primarily in coastal regions or on islands between 20 and 40° of latitude in both hemispheres (Brooke, 2001). In contrast with the tectonically active Baja California peninsula, most carbonate dune fields accumulate in coastal areas that are stable or experiencing slow rates of subsidence (Brooke, 2001). The relatively small dune fields featured in this study occur in low, north-facing regions associated with older coastal basins that formed during the opening of the Gulf.

Examples of the region's carbonate dunes were noted first by Anderson (1950) on the north side of Carmen Island in the lower Gulf and by Ives (1959) on the edge of the Sonoran desert near the head of the Gulf. More recently, Russell and Johnson (2000) described carbonate dunes that are actively accumulating sediment on the north shore of Punta Chivato and related them to seasonal patterns of wind and wave transport in the midriff zone of the Gulf of California. Data on the prevailing winds that blow out of the north between October and April show that the central Gulf region receives peak impact during the winter season with sustained intervals of wind speed commonly registering between 10 and 15

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m/s (BRAY and ROBLES, 1991). El Norte winds are funneled down the length of the Gulf over an enormous fetch and generate huge wave trains that move south to impact north-facing beaches on islands and small peninsulas like Punta Chivato that protrude into the Gulf. The effectiveness of the winter winds is underscored by the widespread occurrence of krummholz trees permanently bent at the ground by salt pruning to point in a southerly direction (RUSSELL and JOHNSON, 2000). The Punta Chivato dune fields were found by RUSSELL and JOHNSON (2000) to have a maximum carbonate content of 76%.

The purpose of this contribution is threefold. The first objective is to extend the same kind of detailed sedimentological analyses performed by RUSSELL and JOHNSON (2000) at Punta Chivato to other coastal dune fields in the region. The second goal is to devise a volumetric model for eolian carbonate sand based on the bivalve mollusk *Megapitaria squalida,* a locally abundant species considered to be one of the most important contributors of calcium carbonate to the regional dune systems. This aspect of the study evaluates the changes in volume that a collection of clams go through as they are mechanically reduced from intact shells to sand-size particles in the laboratory. The third objective is to formulate a method for quantifying the amount of calcium carbonate sequestered in a dune field using the data from the first two phases of the project.

GEOGRAPHIC AND SEDIMENTOLOGIC SETTINGS

Two dune fields located in the northern part of Baja California Sur near Mulegé and San Nicolás (Figure 1A) were chosen for study because of their large size and similar exposure on north-facing shores overlooking the Gulf of California. The dune field situated on the west flank of Cerro El Gallo (Figure 1B) is located 4 km directly southeast of El Sombrerito lighthouse in Mulegé. It is easily visible on the east side of Federal Mexican Highway 1, 6 km from the village center by road. Dirt roads branch off the highway and lead to the north (seaside) and south (inland) ends of this dune field. An unnamed dune field lies behind the beach 4 km east to southeast of the hamlet of San Nicolás (Figure 1C). The dune field is accessible from the estuary at San Nicolás only by four-wheel-drive vehicle following a track along the beach. San Nicolás is reached via a gravel road east from Mexican Highway 1 from Rancho El Rosarito (at kilometer 64).

Figure 1B shows both the active and more stabilized parts of the dune field at Cerro El Gallo. These dunes cover an area of nearly 2 km^2, bounded on the north by the Gulf of California and on the east by the ridgeline of Cerro El Gallo (Rooster Hill). Cerro El Gallo occupies the up-thrust side of a major north–south fault and rises to an elevation of more than 120 m above sea level. The ridge, which is triangular in shape and formed by andesite bedrock, bifurcates the active parts of the dune field. A sequence of three large transverse dunes dominates the inland or southern sector of the dune field. The lee slope of the southernmost dune has a maximum drop of about 21 m and an angle of repose between 28 and 31° (Figure 2A). Figure 1B indicates a barren zone between the southern and northern sectors of the dune field coincidental with the west slope of Cerro El Gallo. Patches of sand form a very thin cover over much of this middle zone and even drape part of the hillside. The northern sector is characterized by a series of partially vegetated dune ridges that start directly behind the beach and gradually rise to an elevation more than 20 m above sea level (Figure 2B). Hummocks of vegetation partially disrupt the organization of the ridges, which become more chaotic farther inland from the beach. The lee slopes of these dune lines have a maximum drop of about 7 m, with an angle of repose similar to those in the southern sector. Partly funneled by Isla El Gallo and Cerro El Gallo (Figure 1B), sand transport occurs in the winter and is exclusively north-northwest to south.

Figure 1C shows the extent of both active and stabilized parts of the dune field near San Nicolás. The estuary at San Nicolás occurs close to a geographic junction where the north–south shore along the base of the Concepción Peninsula turns to form an east–west shore. The dunes near San Nicolás cover about the same surface area as the Cerro El Gallo dune field but the active part, composed of a partially vegetated dune ridge, is constrained to a narrow zone adjacent to the beach. The stoss slopes of these dunes are commonly eroded and reconfigured by storm waves. As at El Gallo, north–south chutes that are controlled by hummocks of vegetation rise through the dunes at various places and help funnel beach sand to the highest parts of the ridge at elevations from 4 to 8 m above sea level. The southern most dunes in the active field have a maximum drop of 7 m on the leeward slope (Figure 3). The depth of sand in the vegetated area is very thin but extends inland up to 1 km, where it can reach elevations of 20–40 m above sea level. Underlying bedrock consists of a silty limestone of Pliocene age that is flat lying or dips seaward at a low angle. As at Cerro El Gallo, sand transport is essentially north to south.

Beaches that directly border the north sides of the dune fields at El Gallo and near San Nicolás are the immediate source of carbonate sand feeding those dunes. A broad, east–west stretch of the beach at the San Nicolás locality is shown at low tide in Figure 4A. The gently sloping, lower half of the beach is still wet in this view. At this stage in the out-going tide, the beach is approximately 30 m wide. Coarse fragments of broken and abraded mollusk shells are scattered over the dry surface of the upper beach (Figure 4B). Abundant, disarticulatated bivalves are mixed together with dark pebbles of andesite volcanics and strewn over the wet surface of the lower beach (Figure 4C). While the detritus of no two tides is ever the same, *M. squalida* is very common on sand flats off the Baja California peninsula and this infaunal species is known to occur offshore to depths of 160 m (KEEN, 1971, p. 178). Called the Chocolata Shell on account of distinctive creamy beige and brown bands, even small shell fragments are readily recognized on this basis as derived from *M. squalida.* The ultimate provenance for the carbonate material sequestered in the dune fields near Mulegé and San Nicolás clearly includes these bivalves and many other mollusks, both infaunal and epifaunal, that are found commonly unbroken on the lower beach.

METHODS AND MATERIALS

Sedimentological analyses performed on dune samples consisted of two operations on a total of 19 samples. The first

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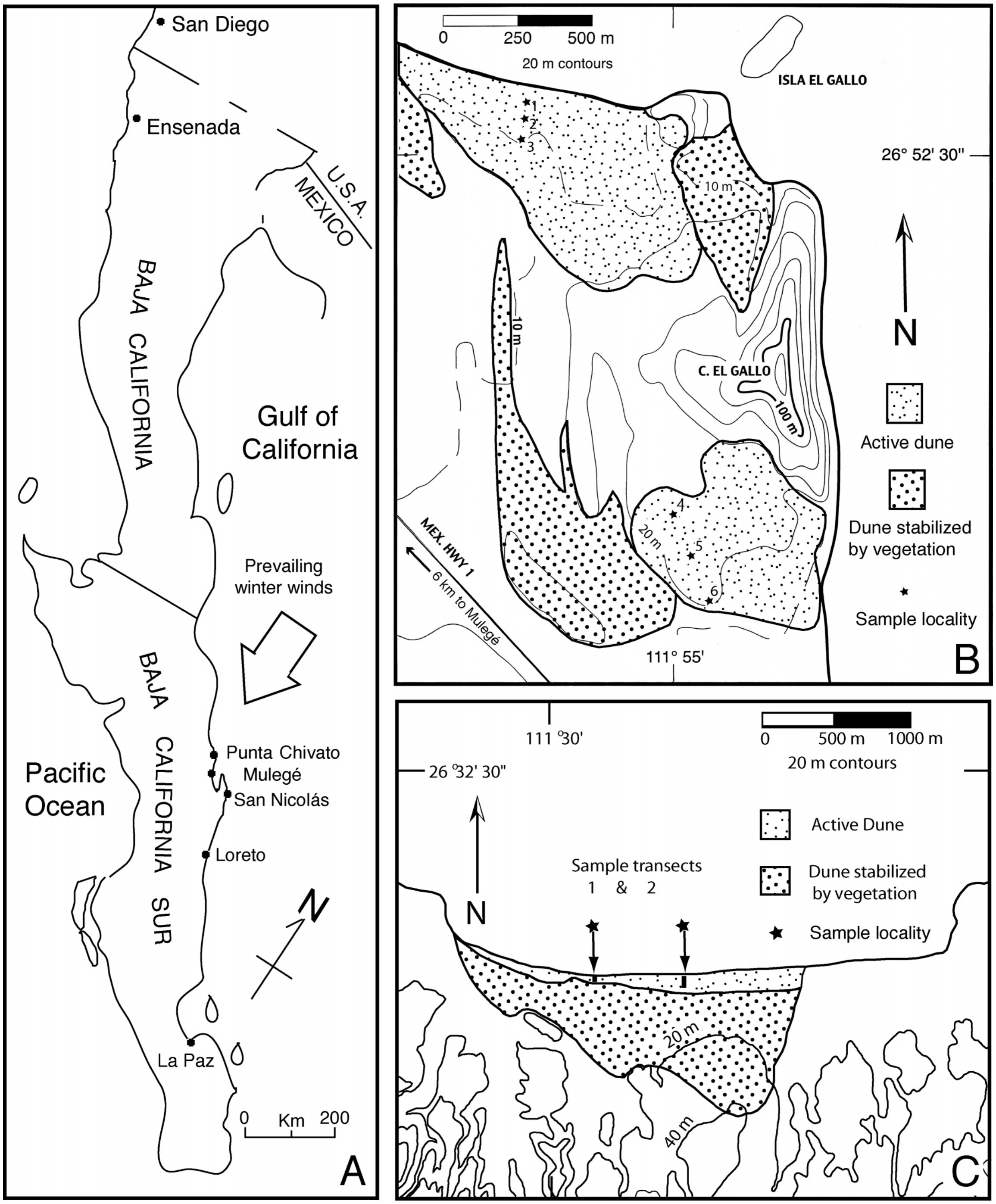

Figure 1. Maps including (A) the Baja California peninsula with places of interest marked at Punta Chivato, Mulegé, and San Nicolás on the gulf shore of Baja California Sur, (B) site map for study area of coastal dunes associated with Cerro El Gallo near Mulegé, and (C) site map for study area of coastal dunes near San Nicolás.

was grain-size analysis using a set of nested sieves and the second was compositional analysis, carried out by point counting of grains in thin sections under a petrographic microscope. The sieving operation was undertaken using a stack of sieves in 0.5-ϕ intervals from −1.5 ϕ to 3 ϕ. Each sample, consisting of about 250 gm of dune sand, was run through a sieve shaker for 20 minutes. The resulting size fractions were weighed so that computations based on cumulative percentages could be calculated for mean grain size, standard deviation, and skewness.

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Figure 2. Dune field at Cerro El Gallo showing the steep leeward face of more inland sand bodies with maximum height of 21 m (A), and near-shore sand bodies with maximum height of 7 m on the leeward face (B). View over the inland dunes is to the southwest with foothills of the Sierra de Guadalupe in background; view over the shore dunes is to the northwest with mouth of the Mulegé estuary in the distance. **For color version of this figure, see page 602.**

In order to quantify dune-sand composition, samples of unconsolidated sediment were transformed into rock using an Embed-It™ low-velocity epoxy kit from Polysciences, Inc. The samples were cured in ice-cube trays, from which slips for the cutting of thin sections were trimmed. Point-count data were collected using a petrographic microscope outfitted with a Swift mechanical stage attached electronically to a Prior automatic point counter. With the exception of a single sample that contained larger grains, all thin-section samples yielded a minimum tally of 400 counts on individual grains. This number of counts is considered adequate to provide data within the 5% confidence interval (Van Der Plas and Tobi, 1965). Bioclastic grains were divided into four categories: bivalve mollusk, coralline red algae, sea urchin, and unknown. The original reference materials used by Russell and Johnson (2000) consisted of crushed shells of known organisms embedded in epoxy, from which petrographic thin sections were cut. These samples were consulted prior to and during registration of the point counts. Other grains were divided into nine categories that include limestone lithic, volcanic lithic, feldspar, undifferentiated feldspar, orthoclase, plagioclase, quartz, dark minerals, and amphibole/pyroxene. Dark minerals included mostly the opaque minerals, biotite, olivine, and epidote.

Experimental data were collected on the sedimentary volume of calcium carbonate derived from the shells of *M. squalida*. The materials used in this phase of the project came from two sources. Sufficient whole shells were collected from a modern midden at Punta Bajo, near Loreto on the gulf coast of Baja California (see Figure 1A), to assemble matched valves for 49 individuals. Another 26 whole clams were acquired from a commercial supplier in Ensenada. Thus, a total population of 75 articulated shells of *M. squalida* from the Gulf of California was dedicated to the experiment. Each pair of shells was measured on three axes using vernier calipers and weighed using an electronic balance. A selection of clams in different size categories also was examined in order to measure volume taking into account the living cavity. This was accomplished by wrapping clams in parafilm and submerging them under water in a large graduated cylinder to find the volume of displaced water. The measurement of decreasing volume of shell material under progressive stages of mechanical disaggregation was accomplished using a specially constructed box with internal dimensions of 25 cm to each side. The four walls of this box were inscribed on the inside to measure the depth of fill material on a centimeter scale.

The ontogenetic age of typical *M. squalida* shells was established in two ways. First, age in years was estimated by examining growth lines expressed as dark rings on the outside of each valve. Second, stable oxygen isotope ($\delta^{18}O$) samples were taken from two specimens of *M. squalida* collected from Punta Baja north of Loreto. In the lab, shells were sectioned along the dorso-ventral axis of maximum growth. Samples were drilled in the outer prismatic layer from the umbo (area of articulation) to commissure (edge of closure). Carbonate isotopic analysis was performed on a Finnigan MAT 252 mass spectrometer equipped with a KIEL III automated sampling device. Samples were reacted with >100% ortophosphoric acid at 70°C. Repeated measurement of standard carbonates resulted in standard deviations of ±0.08‰.

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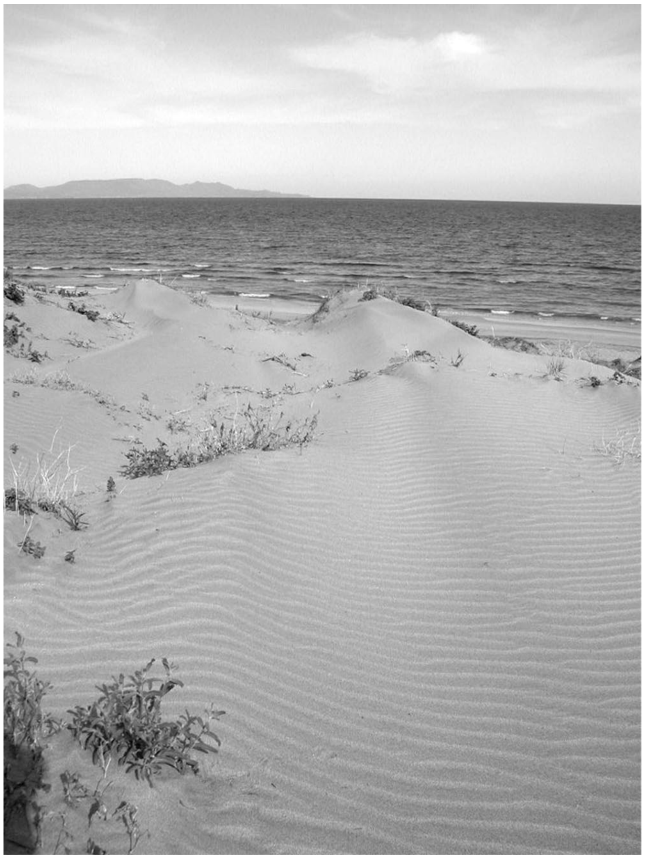

Figure 3. Formation of sand ripples near the crest of the dune field (viewed to the north-northwest) near San Nicolás.

Results are presented in permil notation with respect to the V-PDB carbonate standard.

Figures 1B and 1C were drafted using topographic maps from the Mulegé and San Nicolás sheets produced by the Mexican government (Instituto Nacional de Estadistica Geografica e Informatica) at a scale of 1 : 50,000 (map indices G12A57 and G12A68, respectively) and updated by LANDSAT and ASTER satellite images.

RESULTS OF SIEVE AND COMPOSITIONAL ANALYSES

Cerro El Gallo Dune Field

Sample collection sites along transects in the active north and south dunes of the Cerro El Gallo dune field are marked on the map in Figure 1B. Three samples, EG-1 to EG-3, were collected at intervals over a 60-m transect parallel to the axis of the local dominant wind direction (north to south) in the north field. The first sample was taken just above the beach at the base of the first dune. Three samples, EG-4 to EG-6, and a supplemental sample, EG-6A, from the trough adjacent to sample EG-6 on a dune crest, were collected at the crests of the three large transverse dunes that dominate the south field on a 200-m transect. Results for the mechanical sieve analysis are grouped and averaged by area (near shore *vs.* inland) in Table 1. The data show that grain size decreases slightly with distance from the beach. That is, the average grain size for all cumulative percentage bins computed is smaller farther from the beach than it is close to the beach. The overall mean grain size is also smaller for samples farther from the beach (2.3 ϕ or 0.21 mm) than for samples near the beach (2.01 ϕ or 0.25 mm). The standard deviation is higher (0.65 ϕ) for samples closer to the beach than for samples farther away from the beach (0.50 ϕ). This qualifies the samples as moderately well sorted to sorted and indicates that the samples more distal from the beach are better sorted than those proximal to the beach. Samples closer to the beach exhibit an average skewness value of -0.91 ϕ, which is much larger than the skewness value for the more inland samples (-0.20 ϕ). This result indicates the presence of a more robust coarse tail closer to the beach.

Table 2 provides data regarding the composition of dune samples through the two transects at Cerro El Gallo. Lithic and terrestrial mineral grains clearly predominate over bioclastic grains in the dune sediments from this field. Counts from samples collected farther inland yielded an average composition of 94% lithic and mineral grains and only 5% bioclastic grains, while counts from samples closer to the beach yielded an average composition of 88% lithic and mineral grains and 11% bioclastic grains. Unequivocally, bioclastic grains of carbonate material are more abundant in samples found closer to the shore than in samples collected more inland. However, comparison of samples EG-6 and EG-6A with the first sample from the base of dune nearest the beach (EG-1), demonstrates that carbonate sand grains can be concentrated along low points in the crests of inland dunes. More than 80% of the bioclastic grains of calcium carbonate identified in thin section from the Cerro El Gallo dune field were derived from mollusks.

San Nicolás Dune Field

Sample collection sites along parallel transects perpendicular to the shore in the coastal dunes near San Nicolás are marked on the map in Figure 1C. The two transects are separated by about 700 m, with the first sample in each line taken just above the beach at the base of the first dune. Four samples were collected in the first transect, SN1-1 to SN1-4, at 10-m intervals moving inland and including a supplemental sample, SN1-4A, taken in a low channel along the crest line that locally acted as a funnel for the wind. Seven samples were collected in the second transect, SN2-1 to SN2-7, also at 10-m intervals moving inland over a longer dune. The first four of these samples come from the active dune, but the last three are from the back-dune area partly stabilized by vegetation.

Results for mechanical sieve analyses are presented in Table 3 for transects 1 and 2. There are only slight differences between the two transects. According to the Wentworth scale, the average grain size of sediments along both transects ranges from medium sand to upper fine sand. Average grain size is between 2.29 ϕ and 1.19 ϕ (0.20 mm and 0.25 mm) for all samples except for SN4A, which exhibits an average

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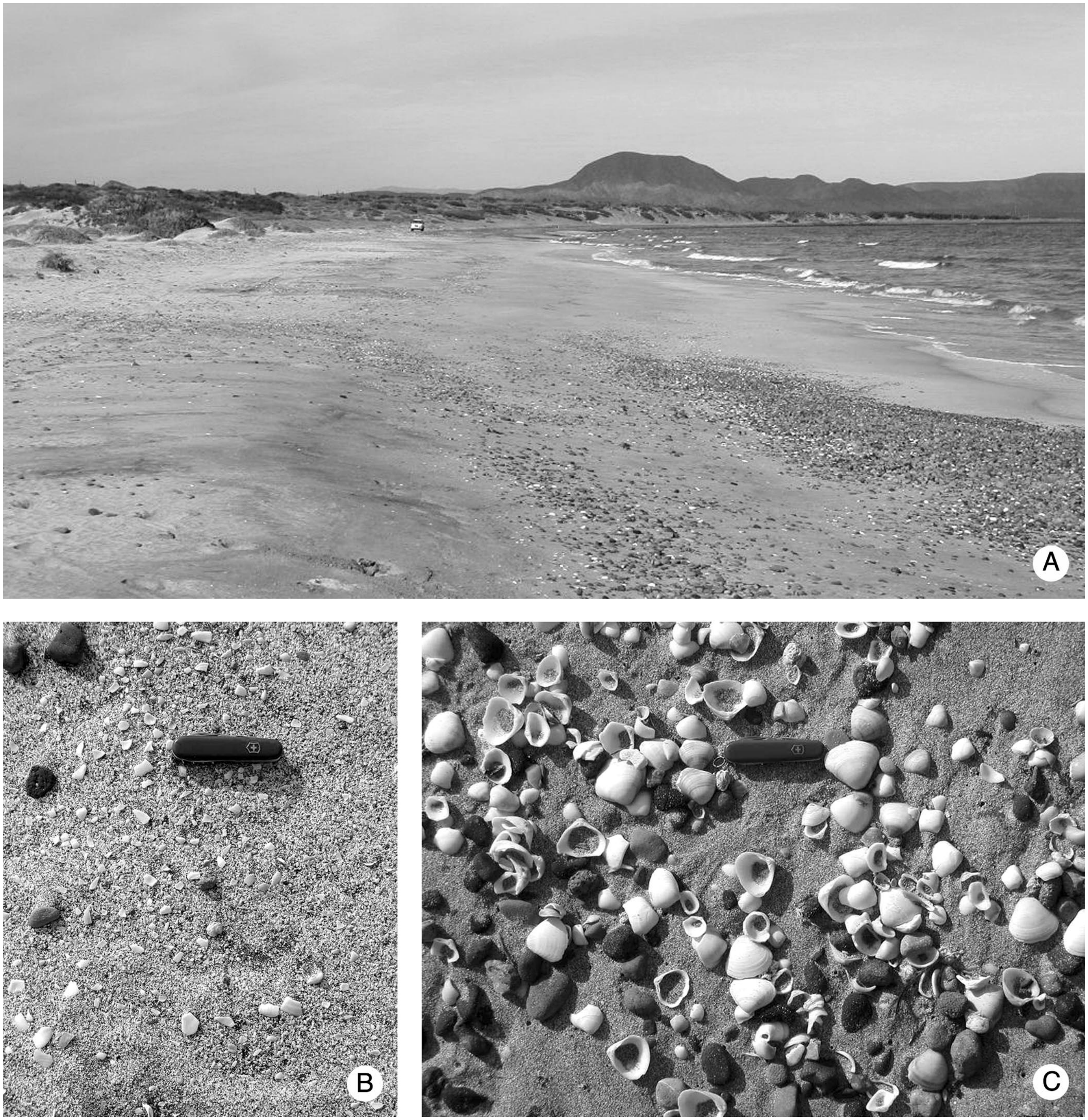

Figure 4. (A) North-facing beach at low tide on the Gulf of California 4 km west of San Nicholas. Approaching pick-up truck in the far distance indicates scale of the beach. (B) Close-up view of upper beach zone showing course fragments of broken shell material. Pocketknife is 9 cm long. (C) Close-up view of lower beach zone showing whole, disarticulated bivalve shells. Pocketknife is 9 cm long.

gain size of 0.65 ϕ (0.64 mm), or coarse sand. Along both transects, sediments become better sorted with increasing distance from the shore. The only exception to this trend is shown by sample SN1-1, which is the best sorted sample in the first transect, but occurs nearest to the beach. This result is anomalous and could be explained by small-scale topographic variations on the beach or by interference from the action of waves during high tides or storm surges. Inclusive for transect 1, the standard deviation ranges from about 0.4 to 0.55 ϕ (well-sorted to moderately well-sorted sand), with

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Table 1. *Elevation and sieve-analysis data for dune samples associated with El Gallo as averaged from two clusters for near-shore as opposed to inland localities.*

Samples (see figure 1B)	Relative Location	Elevation (m)	Mean Grain Size (mm)	Mean Grain Size (Φ)	Standard Deviation	Skewness (Φ)
EG-1, 2, and 3	Near shore	3–9	0.25	2.01	0.65	−0.91
EG-4, 5, and 6	Inland	20–21	0.21	2.30	0.50	−0.20

the noted exclusion of sample SN1-1. Through transect 2, the standard deviation ranges from about 0.45 to 0.7 ϕ (also well-sorted to moderately well-sorted sand). The most notable difference revealed by sieve analysis between the two transects occurs in patterns of skewness. Transect 1 shows evidence of positive skewness with a coarse tail prevalent closer to the beach, but grades into a fine tail (negative skewness) more inland. The second transect records no such pattern.

The results of point-count analyses for transects 1 and 2 are presented in Tables 4 and 5, respectively. These data reflect significantly higher percentages for bioclastic grains of calcium carbonate than found on the Cerro El Gallo dune field. Samples in the first transect show bioclastic fractions that range from 26% to just over 50%, with an average of 33.4%. Values from samples in the second transect are generally higher, with an average bioclastic fraction of 40%. The exception to this trend comes from sample SN1-4A in transect 1 with a calcium-carbonate component of 50.6%, the highest of any sample in either line. As at Cerro El Gallo, the carbonate fraction in these dune fields is dominated by clasts derived from mollusks, principally bivalves.

Sample SN1-4A (Table 5) is interesting both for its high calcium-carbonate content and for its population of relatively large-size grains. The grains captured in the thin section from this sample were so large (mean grain size of 0.65 ϕ, or 0.64 mm) that only 346 clasts could be counted in the space available. The location of the sample in a channel in the dune crest probably benefits from locally higher wind speeds due to funneling. Selection for low-sphericity grains as predicted by WILLIAMS (1964) may contribute to the higher percentage of carbonate grains at this spot. Shore winds on this beach may select for transport of discoid mollusk fragments over more spherical lithic fragments and mineral grains. Winds of such speeds may be less efficient at moving the larger grains to the top of a dune crest and, hence, more transport of larger calcium-carbonate clasts may occur through troughs that penetrate the dune field. Shape sorting as described by MATTOX (1955) could be another important process that affects the sedimentological character of the forward dune fields.

RESULTS OF BIVALVE VOLUME EXPERIMENTS

Keeping in mind that the results of experimental generation of calcium-carbonate sand from bivalves was based on two sources of *M. squalida* combined to make a population of 75 whole clams, the profile of an average individual from this population may be summarized as follows. It has long, intermediate, and short axes of 8.25 cm, 6.44 cm, and 4.17 cm, respectively. The short axis represents shell obesity, or maximum height from one valve through the other. The other two axes reflect maximum dimensions measured perpendicular to one another on a single valve. The model bivalve shell had a volume of 109.3 ml.

Ontogenetic Age of Shells

The ontogenetic age of *M. squalida* was estimated in two ways. First, based on a rudimentary count of major growth lines that follows CLARK (1974, his Figure 3) for the related species of *M. aurantiaca,* the average age of individuals in the composite population was estimated to be 5.27 years. This conclusion is supported by the second method based on $\delta^{18}O$ variation from the two specimens of *M. squalida* (Figure 5) collected at Punta Bajo near Loreto (Figure 1A). In each profile, several cycles are present. These cycles represent annual temperature variation. The empirically determined temper-

Table 2. *Point-count data for sediment samples from dunes associated with El Gallo: Based on a minium count of 400 grains per thin section. No more than 2% of feldspar grains are K-feldspar; most of the rest are plagioclase.*

Grain Type	EG-1 (%)	EG-2 (%)	EG-3 (%)	EG-4 (%)	EG-5 (%)	EG-6 (%)	EG-6A (%)
Mollusk	10	12	6	6	5	3	6
Red algae	0	0	1	0	0	0	0
Sea urchin	0	0	0	0	0	0	0
Unknown biological	5	1	1	1	0	0	0
Subtotal	15	13	8	7	5	3	6
Volcanic lithic	42	50	34	47	42	48	44
Feldspar	27	24	29	29	36	31	31
Pxn + amph	10	5	15	8	5	7	4
Dark mineral	5	7	13	8	10	9	12
Quartz	2	1	1	2	1	2	3
Subtotal	85	87	92	93	95	97	94
Total	100	100	100	100	100	100	100

Table 3. *Elevation and sieve-analysis data for dune samples on transects 1 and 2 in the San Nicolás area (see Figure 1C for map).*

Sample (see Figure 1B)	Elevation (m)	Mean Grain Size (mm)	Mean Grain Size (Φ)	Standard Deviation	Skewness (Φ)
SN1-1	1.0	0.20	2.17	0.78	−1.90
SN1-2	1.5	0.19	2.05	0.37	0.15
SN1-3	2.0	0.21	2.25	0.55	0.40
SN1-4	2.5	0.21	2.23	0.46	0.25
SN1-4A	2.5	0.51	0.65	0.55	1.58
SN2-1	1.0	0.21	2.20	0.47	−0.38
SN2-2	1.5	0.10	2.29	0.44	−0.14
SN2-3	2.0	0.20	2.14	0.42	0.10
SN2-4	2.5	0.20	2.12	0.45	0.03
SN2-5	2.5	0.20	2.15	0.58	−0.39
SN2-6	3.0	0.21	2.23	0.54	−0.18
SN2-7	3.5	0.25	1.99	0.69	−0.79

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Table 4. *Point-count data for sediment samples from dunes associated with transect 1 near San Nicolás: Based on a minimum count of 400 grains per thin section. No more than 2% of feldspar grains are K-feldspar; most of the rest are plagioclase.*

Grain Type	SN1-1 (%)	SN1-2 (%)	SN1-3 (%)	SN1-4 (%)	SN1-4B (%)
Mollusk	25	25	30	24	46
Red algae	0	0	3	1	1
Sea urchin	1	0	1	1	0
Unknown biological	3	1	1	0	4
Subtotal	29	26	35	26	51
Limestone lithic	0	0	1	1	2
Volcanic lithic	32	26	33	26	31
Feldspar	16	28	22	25	7
Pxn + amph	15	13	4	13	7
Dark mineral	7	4	3	8	1
Quartz	1	1	1	0	1
Subtotal	71	74	64	73	49
Total	100	100	100	100	100

ature relationship for biogenic aragonitic carbonates established by Grossman and Ku (1986) suggests that a one-permil shift in $\delta^{18}O$ shell carbonate reflects a 4.34°C change in temperature. Based on the maximum $\delta^{18}O$ variation in each shell (most positive value minus the most negative value), the temperature variation experienced was 9.8°C and 8.8°C for Ms-1 and Ms-2, respectively. It is important to point out, however, that oxygen isotope values from biogenic carbonates also are a function of the water in which the clams grew. An annual variation in $\delta^{18}O$ cycles of greater than 2‰ is required to show definitively that the cycles are being driven by seasonal changes in water temperature. For the $\delta^{18}O$ cycles present in Ms-1 and Ms-2 to solely reflect changes in the isotopic composition of the water requires an annual variation greater than 2‰. This value is nearly twice the $\delta^{18}O$ water variation observed in the hyperarid Colorado River delta in the northern Gulf of California (see Goodwin *et al.,* 2001). Furthermore, based on salinity observations, Thunell *et al.* (1999) calculate constant $\delta^{18}O$-water values throughout the year for the Guaymas Basin centered 80 km east of Mulegé.

These observations suggest that the $\delta^{18}O$ variation shown in Figure 6 reflects annual temperature variation and can be used to estimate the ontogenetic age of each specimen. Using this approach, it can be assumed that Ms-1 was approximately 2.5 years old at the time of its death and Ms-2 was about 3.5 years old. These values are consistent with the growth-line estimate discussed above and support the assessment that *M. squalida* typically lives at least 3–5 years. Furthermore, this estimate is likely conservative due to the onset of senescence, which results in coalescence of growth lines and muted isotopic variation (for discussion, see Goodwin *et al.,* 2003).

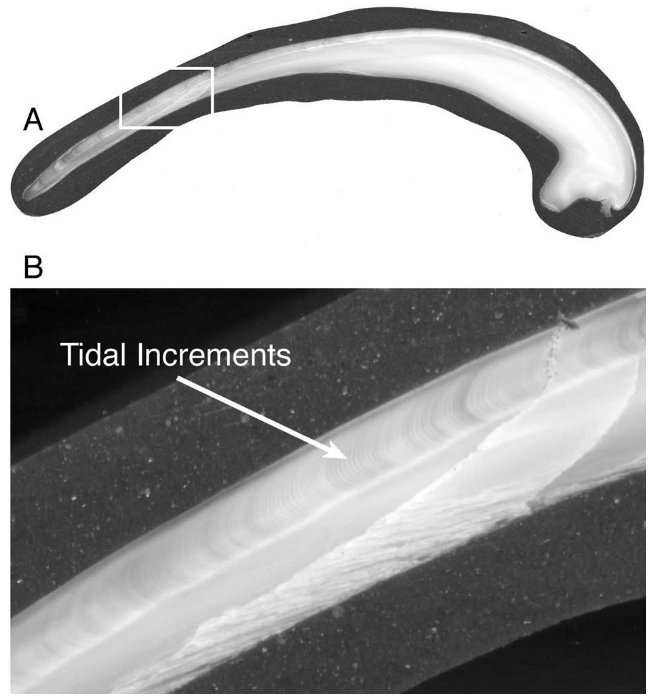

Figure 5. Dorso-ventral cross sections through *Megapitaria squalida.* (A) Section from the umbo to the commissure along the axis of maximum growth, (B) enlarged view of a ventral portion of the shell in A. Note the clearly visible tidal increments in the outer shell layer. The shell height in A is 8 cm and the enlarged image is 1 cm wide.

Table 5. *Point-count data for sediment samples from dunes associated with transect 2 near San Nicolás: Based on a minimum count of 400 grains per thin section. No more than 2% of feldspar grains are K-feldspar; most of the rest are plagioclase.*

Grain Type	SN2-1 (%)	SN2-2 (%)	SN2-3 (%)	SN2-4 (%)	SN2-5 (%)	SN2-6 (%)	SN2-7 (%)
Mollusk	32	38	43	37	32	30	39
Red algae	3	0	1	1	2	3	2
Sea urchin	0	0	1	2	3	1	1
Unknown biological	1	2	3	0	1	1	1
Subtotal	36	40	48	40	38	35	43
Limestone lithic	0	1	1	2	1	1	1
Volcanic lithic	33	29	23	27	30	33	21
Feldspar	26	21	18	22	22	22	24
Pxn + amph	2	2	2	4	5	4	5
Dark mineral	2	3	5	4	3	3	3
Quartz	1	2	2	0	0	1	1
Unknown	0	2	1	1	1	1	2
Subtotal	64	60	52	60	62	65	57
Total	100	100	100	100	100	100	100

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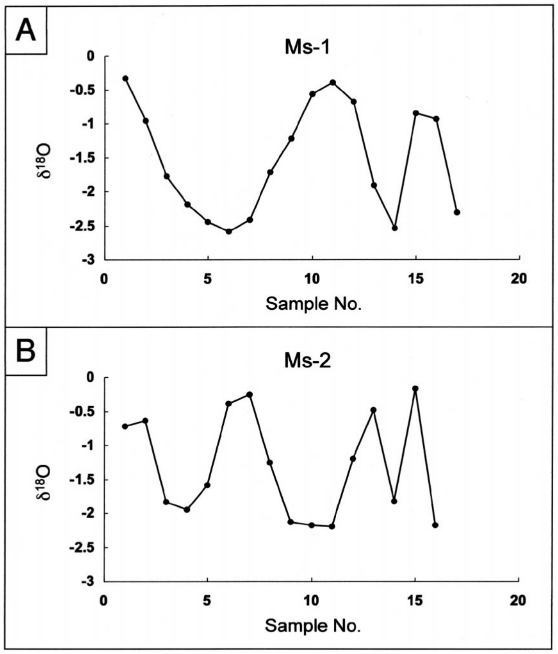

Figure 6. Stable oxygen isotope profiles from two specimens of *M. squalida.* Isotope samples were collected from the umbo to the commissure and time passes from left to right in each graph (A and B). See text for discussion.

Volume of Articulated Shells

As a starting point, it was determined how many articulated bivalves of mature *M. squalida* are required to fill a space of 1 cubic meter. Examples of bivalves from the fossil record are well known to occur fully articulated and in growth position. One of the earliest descriptions comes from the notebooks of Leonardo Da Vinci, who clearly recognized fossil populations preserved intact in the mountains of Lombardy and realized that age at time of death could be crudely determined by counting major growth lines (CLARK, 1974; EDWARDS, 1976). Indeed, bivalves that date from the Pleistocene and Pliocene in the Gulf of California are known to form extensive banks, where succeeding generations occupied the same place and left behind enormous populations often preserved in life position (JOHNSON, 2002). In order to estimate the number of *M. squalida* in a cubic meter, 35 trials were carried out to experiment with various ways of handpacking the articulated shells into the box measuring 25 cm on each side. Sometimes the clams were packed flat, sometimes on edge (wedged downward in normal position), and sometimes on their ends (posterior side of the umbo, downward). Sometimes the largest clams were placed on the bottom and other times the smallest individuals were placed on the bottom. Yet other times, the larger and smaller clams were laid down in alternating layers. The clams were also packed opportunistically wherever space was available. In each trial, the top layer was rearranged to be as flat as possible so that the maximum height reached by the mass of articulated clams could be measured against the walls of the box using a cardboard cap cut to fit inside the box.

The average level to which the sample population of 75 *M. squalida* filled the box in 35 trials was 21.2 cm, with a standard deviation of 0.62 cm. From this outcome, it can be determined by a simple ratio that 88 ± 2.5 whole clams are required to completely fill the test box, which represents 1 out of 64 such blocks in a cubic meter. Thus, 1 cubic meter will accommodate approximately 5632 articulated bivalves of mature *M. squalida.* In life, no such concentration could be expected because the species is fully infaunal in habit.

Volume of Disarticulated Shells

Packing of whole but disarticulated shells within the test box allows many more shells to be added to the same space, particularly when most of the valves are nested against one another with concave surfaces against concave surfaces (Figure 7A). Manipulation of the experimental numbers shows that it requires approximately 14,634 single valves of *M. squalida* to effectively occupy 1 cubic meter as a pure shell coquina. This number also represents the equivalent of 7317 articulated individuals, which amounts to 1685 more individuals than required to fill a cubic meter with articulated shells alone. Thus, the packing of disarticulated shells permits a roughly 30% increase in the number of articulated clams that can be accommodated by a cubic meter.

Volume of Crushed Shells

Two levels of crushing were undertaken to further reduce the space occupied by the population of 75 individuals of *M. squalida.* The first reduction was accomplished by manually breaking the disarticulated shells into nickel-and-dime-size bits with a rock hammer until they resembled the very coarse beach material described by RUSSELL and JOHNSON (2000) on the Ensenada El Muerto of the Punta Chivato promontory. The second crush was achieved by milling this product using a Bico-type UA pulverizer until it was reduced to the size range from fine to coarse sand mixed with shell fragments less than 5 mm in diameter (Figure 7B). Again, manipulation of the experimental numbers shows that it would require approximately 12,000 articulated bivalves in order to supply enough material from the first crush to fill 1 cubic meter with carbonate beach sand. This represents something on the order of a 113% increase in the number of articulated clams that can be accommodated by a cubic meter. For the second, more thorough crush, the numbers suggest that it would require at least 15,650 articulated clams to undergo an equivalent reduction sufficient to occupy 1 cubic meter. This calculation represents an almost 180% increase in the number of articulated clams that can be fit into a cubic meter, and it is our closest approximation to the bulk material needed to produce a cubic meter of carbonate dune sand.

Estimation of Dune Volume, Bivalve Enrichment, and Carbon Input

Using satellite images for the dune fields near Mulegé and San Nicolás, the perimeters of active dunes may be outlined

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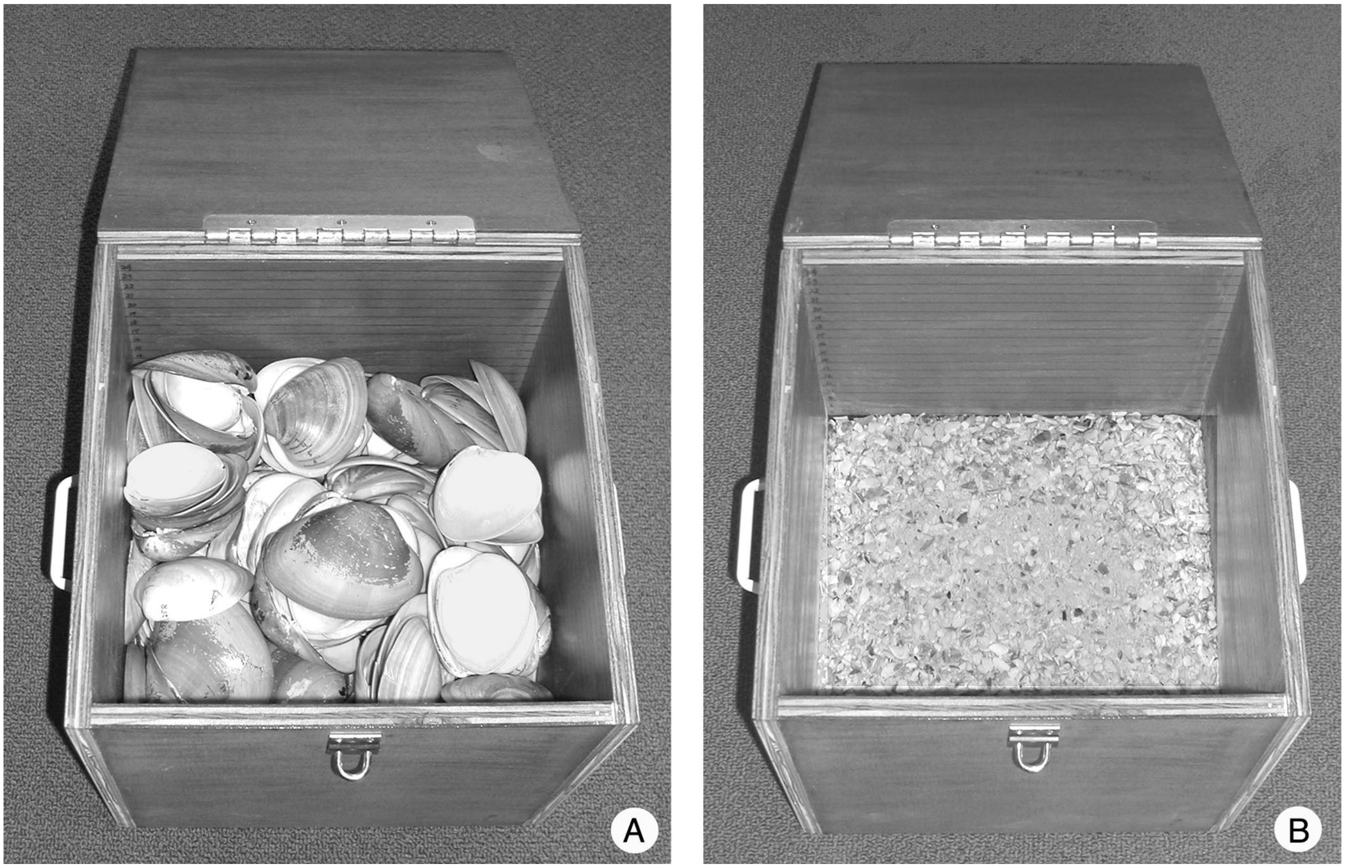

Figure 7. Experimental apparatus used to calculate the volume occupied by intact but disarticulated shells (A) as opposed to crushed shells (B) consists of a box with internal dimensions that measure 25 cm on each side. The chamber's four side walls are ruled in centimeter increments.

and the surface areas roughly calculated. False-color images generated from ASTER data (15 m/pixel resolution) using bands 8, 3, 1 and modified by a linear 2% stretch were used to view the dune field. In this combination of bandwidths, carbonate sediments clearly stand out from the surrounding country rock. Dune field areas were calculated using the measurement tool in the remote-sensing ENVI 4.1 software package. As noted previously, the Cerro El Gallo dune field includes two active dune areas (Figure 1B). The northern area of dunes is estimated to cover 65 hectares, or 650,000 m^2, while the southern, more inland dune area covers 42 hectares, or 420,000 m^2. Likewise, the active dune field near San Nicolás is estimated to cover only 10 hectares, or 10,000 m^2.

Knowing the maximum thickness of these dunes, it is possible to arrive at a crude estimate for the number of cubic meters of dune sand in each field. Bearing in mind that eolian deposits are characterized by a gentle stoss slope in the windward direction and a steep leeward slope, a rudimentary transformation from surface area to volume may be reached by accepting the average thickness of a given dune as one half the maximum dune height. In other words, the stoss slope is represented in a cross section of any dune as a diagonal line that rises from a zero point to the maximum height of the dune front on its leeward side. Thus, the cross-sectional area of a dune may be represented by a triangle that is one-half of a rectangle with the short axis fixed by maximum dune height and the long axis by the ground length of the dune. In this way, the volume of dune sand in the northern part of the field at Cerro El Gallo is estimated to be 2.3 million cubic meters and the volume of dune sand contained in the southern field is 4.2 million cubic meters. When the rather low average composition of calcium carbonate material from mollusks in these dunes is taken into account (see previous section), it is concluded that the northern dune at Cerro El Gallo has incorporated 212,000 cubic meters of shelly material, while the southern dune retains a lesser amount of 197,400 cubic meters. In contrast, the higher sequestration rate of carbonate sand in the active dune field near San Nicolás suggests that 113,750 cubic meters out of a total of 350,000 million cubic meters in that active dune field is calcium carbonate sequestered from seashells.

Once the volume of the shell material present in any given dune is known, the amount of carbon present in that dune can be estimated using a relatively straightforward formula. We assume that the calcium carbonate from bivalve mollusks is composed of aragonite, which has a density of 2.93 kg/l. Knowing that the molar mass of calcium carbonate is 116.09 gm, the number of moles of calcium carbonate in the dunes

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can be calculated using the following formula: moles = (V_s × 2932)/0.11609, where V_s stands for the volume of the shell material. Because there is one mole of carbon in every mole of calcium carbonate, the number of moles of carbon sequestered in any given dune field is the same as the number of moles of calcium carbonate present. To obtain the mass of the carbon in a dune field, the number of moles of carbon is multiplied by 112.01 g/mol, the molar mass of carbon.

Combined, the two active dune fields at Cerro El Gallo have sequestered approximately 1.16×10^6 metric tons of carbon derived from the equivalent of about 6.41 billion articulated *M. squalida.* At San Nicolás, the dune field holds an estimated 3.20×10^5 metric tons of carbon from the break down of approximately 1.77 billion clams.

DISCUSSION

Variability of Carbonate Content in Dunes

What possible factors account for the notable differences in calcium carbonate enrichment registered by dune fields at Punta Chivato (Russell and Johnson, 2000) as compared with dune fields in the vicinity of Mulegé and San Nicolás? The frontal dune fields on the Ensenada El Muerto near Punta Chivato are almost twice as rich in calcium carbonate than the dunes near San Nicolás. Dune fields sheltered from the Ensenada El Muerto by a 60-m high ridge are still somewhat richer in calcium carbonate compared with the dunes near San Nicolás. When comparisons with the northern or frontal dunes of Cerro El Gallo are made, the differences are even more striking. The frontal dunes on the Ensenada El Muerto are nearly nine times as rich in calcium carbonate as the frontal dunes of Cerro El Gallo. The richest concentration of calcium carbonate in the dune fields near San Nicolás is at least four and a half times as much as the richest parts of the Cello El Gallo dune fields.

The amount of east–west shoreline abutting the dune fields is one of the more important factors that controls landward input of calcium carbonate material. East–west beaches are perpendicular in orientation to the winter El Norte winds. Beach width in an east–west orientation also bears a relationship to the potential size of the offshore habitat as a source of mollusk debris that accrues first on the beach and eventually in the dunes. From Punta Chivato westward, the Ensenada El Muerto runs 4 km in a straight line and the longest beach is about 1.5 km in length. The beach frontage at Cerro El Gallo is not as extensive as Punta Chivato and is less perfectly placed in an east–west orientation (Figure 1B). Beach size and orientation adjacent to the dune fields near San Nicolás appear to be optimal for capture of shelly material (Figure 1C), but the area of the offshore shallow shelf is much less than found on the Ensenada El Muerto.

Proximity of dune fields to freshwater outlets that affect growing conditions on the mollusk banks is another aspect to take into account. Too much fresh water with runoff onto the shell banks will adversely affect the size of marine mollusk populations. The dune fields that border the Ensenada El Muerto are located 8 km east of the San Marcos estuary, which has a drainage area of about 25 km². The streams that feed the estuary are ephemeral and a shelly sand bar typically closes the mouth of the estuary. Likewise, streams that feed the San Nicolás estuary and adjacent coastline are ephemeral. In contrast with the San Marcos estuary system, the catchment area draining the San Nicolás region is about 65 km² in size. This includes the San Nicolás estuary and smaller arroyos, some of which cross the dune field. The San Nicolás estuarine and arroyo system also extends to the south, through the mountains, and drains an interior basin approximately 75 km² in area. However, it is unlikely this region is the source of any sediment transported to the coast on an annual or decadal time scale. Significant sediment discharge into Bahia San Nicolás is primarily from the coastal catchment area and only occurs during severe storms.

Runoff from major storms probably has a deleterious effect on the health of shellfish in coastal waters, but such storms are infrequent. On average, the entire Baja California peninsula has a mean annual precipitation of 15.3 cm. For the desert region along the midriff of the Gulf of California, however, the mean annual precipitation is only about 5 cm (Roberts, 1989). Against this harshly xeric backdrop, the Mulegé estuary is prominent. The Mulegé River is one of the few streams in the entire Baja California peninsula that runs continuously through the year. It is spring fed, and the channels that connect to the Mulegé estuary drain an area of approximately 250 km². Tides affect the depth of water at the mouth of the Mulegé estuary, but it is open to small boat traffic year round. The northern or frontal dune field at Cerro El Gallo is situated only 4 km southeast of the entrance to the Mulegé estuary.

The third factor that must be taken into account as a likely detraction to the accumulation of shelly material in the coastal dune fields has to do with the amount of exposed volcanic rock in the vicinity. Isla San Marcos, which is predominantly andesite, lies 12 km northwest of the dune fields along the Ensenada El Muerto. This is too far away to impact the Punta Chivato dune fields. The comparatively small amount of volcanic detritus that reaches these dunes undoubtedly comes from the rocky shores that more immediately bracket the Enseanada El Muerto between Puntas Chivato to the east and Elis to the west. Tuffaceous rocks and other poorly consolidated volcanics are well exposed around Mulegé and are prone to subaerial erosion. This material is delivered by longshore transport to El Gallo beach and likely is the source of the bulk of the dune sands at Cerro El Gallo. In addition, a portion of the volcanic detritus is derived more locally from the poorly vegetated slopes of Cerro El Gallo that rise well above the surrounding coastline. As noted above, the village of San Nicolás and the adjacent dune fields sit within a coastal basin of Pliocene age that is drained by the San Nicolás estuary as well as numerous smaller arroyos (Johnson and Ledesma-Vázquez, 2001). Activated by large winter storms, the material delivered to the coast via these arroyos is transported from west to east along the coast by long-shore transport and provides the material for the noncarbonate fraction of the dune sands.

Habitat Suitability as a Viable Carbonate Source

What is the average population density of *M. squalida* in its habitat and is it prolific enough to supply a significant

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part of the carbonate sand accrued by the coastal dunes on the Gulf of California? The only data available on the population density of this species in the region comes from a study by VILLALEJO-FUERTE *et al.* (1999). Live census counts were made using SCUBA equipment in the Bay of Loreto National Park, located near the town of Loreto about 110 km south of Mulegé (Figure 1A). Counts were made on transects that extended 500 m from the beach perpendicular to the shore, but each transect also was crossed by three 20-m lines at right angles. Main transects extended seaward to a depth of 12 m. The average density of *M. squalida* was found to be 1.47 individuals/m^2. Densities were reported as somewhat lower than the average in water less than 6 m deep and somewhat higher at greater depth.

If the average density were characteristic over much of the depth range for the species, then the standing crop for *M. squalida* may be calculated for areas within the 50-m isobath offshore Cerro El Gallo and San Nicolás, as demarked by SHEPARD (1950). Although the maximum depth range for this species is reported to be 160 m by KEEN (1971, p. 178), populations living above the 50-m isobath are more susceptible to wave agitation and transport after depth. Based on a conservative estimate of 75 km^2 for the habitat area immediately north of Cerro El Gallo, the population of *M. squalida* living there could be as high as 110 million individuals (at 1.47 million/km^2). Using a more generous estimate of 200 km^2 for the habitat area, the size of the population could be in the neighborhood of 294 million individuals. As shown above, the equivalent number of *M. squalida* sequestered in the Cerro El Gallo dune field is more than 6 billion individuals. The number of individuals needed to enrich the Cerro El Gallo dune field in its present state would take only 20 generations based on the larger estimate of habitat area, or 56 generations based on the smaller estimate.

Based on a conservative estimate of 10 km^2 for the habitat area immediately north of the dune field near San Nicolás, the population of *M. squalida* living there could be as high as 14.7 million individuals. The more generous estimate of 30 km^2 for the habitat area could represent a population of 44.1 million individuals. As shown above, the equivalent number of *M. squalida* incorporated in the San Nicolás dune field is about 1.77 billion individuals. Depending on the size of the true habitat area, the number of individuals necessary to enrich the dunes in their present state would take only 4–12 generations to accumulate.

While the maximum life cycle of *M. squalida* is only about 5 years, recruitment of cohort groups is likely to be on an annual basis. This shows that, under present rates of productivity, the time needed to enrich the Cerro El Gallo and San Nicolás dune fields is geologically insignificant. Of course, much of the mollusk-derived material remains buried in the seabed or stays on beaches. Also, an unknown fraction of shelly material is dissolved back into the seawater from which mollusks and other marine invertebrates precipitate calcium carbonate as they grow. While the amount of carbon sequestered in coastal dune fields is relatively small compared with the huge number of bivalves available in offshore clam banks, the longevity of carbon from this source held in the dunes is geologically significant. As described by RUSSELL and JOHNSON (2000), lithified dunes of Pliocene and Pleistocene age are well documented in the Punta Chivato area. They also are known to occur elsewhere in the Gulf of California, such as on Isla Carmen (ANDERSON, 1950). Recycling of carbon from dune fields on the Baja California peninsula occurs primarily as a result of ephemeral streams in arroyos that cut through Recent and Neogene deposits and carry sediment back to the Gulf of California.

Carbonate Dunes and Relation to the Carbon Cycle

The dune fields of Punta Chivato, Cerro El Gallo, and San Nicolás are relatively small compared with many of the Quaternary eolianite carbonate deposits reviewed by BROOKE (2001) on a global basis, but they do act as a sink for a modest amount of carbon on a time scale linked principally to glacio-eustatic sea-level changes. The total amount of carbon estimated to be sequestered at Cerro El Gallo is on the order of 11.6×10^{11} g, with an additional 3.2×10^{11} grams estimated for the dunes of San Nicolás. For comparison, the amount of dissolved inorganic carbon in the world's oceans is estimated at 38×10^{18} g, while the reservoir of carbon held in sedimentary rocks is on the order of 60×10^{21} g (BERNER, 1989; FALKOWSKI *et al.,* 2000; HEDGES and KEIL, 1995; OLSON *et al.,* 1985).

If the total amount of carbonate dunes and eolianites found on the earth's surface is taken into consideration, however, these deposits constitute a significant amount of carbon sequestered near modern-day sea level. The amount of carbon found in a dune field is directly related to the carbonate content of the dune sediments. Many of the world's major carbonate dune fields have much larger percentages of carbonate in their sediments than found at Cerro El Gallo (5–15%) or San Nicolás (26–51%). For example, the earth's largest carbonate eolianite deposit found in southeastern Australia has a range for the carbonate fraction of between 50 and 90% of the dune sand (BROOKE, 2001; MCKEE and WARD, 1983). Analyses of coastal dunes from India suggest that carbonate content within a dune field grades from >90% near the coast to around 50% more inland (BISWAS, 1971). Other dune fields and eolianite deposits from coastal Libya, Rottnest Island in Australia, and the Bahamas have carbonate contents mostly in excess of 90% (HEARTY, 2003; MCKEE and WARD 1983).

Another interesting consideration is that coastal deposits of eolianites have the potential to be reintroduced into the oceanographic system and affect the earth's global carbon budget. Most of the reported carbonate eolianite deposits and active dune fields are Pleistocene or Holocene in age, having developed during the glacial–interglacial cycles of the past 500,000 years (BROOKE, 2001; MCKEE and WARD, 1983; MURRAY-WALLACE *et al.,* 2001). Time of sequestration for carbon in dunes depends on the rate of recycling through various geologic processes. Burial locks away carbon for periods up to millions of years or even hundreds of millions of years based on evidence for eolianites of Paleozoic age (HUNTER, 1993; RICE and LOOPE, 1991; SMITH and READ, 1999). In contrast, climatic changes are potentially rapid enough to induce more immediate recycling of coastal dune deposits within the span of 10,000 years or less, due to rising sea level or increased surface erosion.

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CONCLUSIONS

Coastal dune fields in Baja California Sur from the midriff area of the Gulf of California show variable enrichment in calcium carbonate. Adjacent beaches are the immediate source for shelly material deposited in the dunes due to inland transport by northerly winter winds that cause beach deflation. The dunes at Cerro El Gallo near Mulegé are carbonate poor (5–15%) in comparison with those near San Nicolás (26–51%). Both of these localities are impoverished in carbonate content compared with the 76% carbonate material in a coastal dune at Punta Chivato. Clam banks are the ultimate provenance of shelly material that reaches dunes with a northern exposure. One of the region's prolific bivalves, *Megapitaria squalida,* provides the basis for an experimental model that estimates the number of individuals of a given size and age required to generate a cubic meter of pure carbonate sand to be roughly 15,650. The growth rate and size of habitat area for this infaunal species living at water depths $\leq$50 m is more than sufficient to insure a steady source of shelly material for carbonate beaches and dunes.

In determining the average enrichment level for a particular dune field based on direct examination of dune samples and by making an estimate of dune volume based on satellite images together with ground intelligence, it is possible to arrive at a crude estimation of the number of bivalve individuals that undergo *postmortem* transport and reduction as a contribution to dune development. Further, it is possible to calculate, within an order of magnitude of correctness, the amount of carbon sequestered in a given dune field. Attempts have been made to estimate the carbon reservoir held in sedimentary rocks (FALKOWSKI *et al.,* 2000; OLSON *et al.,* 1985), but no effort has been made to differentiate the smaller carbon reservoir sequestered by coastal dune fields. Use of satellite images provides the ready means to search for and identify carbonate dunes in coastal territories, especially where logistics make it difficult to reach remote localities. The gulf coast of the Baja California peninsula makes an attractive target for this kind of exploration aimed at better understanding carbon flux on a regional scale in a physically dynamic setting. This project tests the feasibility for such a program.

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LITERATURE CITED

ALVAREZ-BORREGO, S., 2002. Physical oceanography. *In*: CASE, T.J.; CODY, M., and EZCURA, E. (eds.), *A New Island Biogeography of the Sea of Cortés.* Oxford, UK: Oxford University Press, pp. 41–59.

ALVAREZ-BORREGO, S. and LARA-LARA, J.R., 1991. The physical environment and primary productivity of the Gulf of California. *In*: DAUPHIN, J.P. and SIMONEIT, B.R.T. (eds.), The gulf and peninsular provinces of the Californias. *American Association Petroleum Geologists Memoir,* 47, 555–568.

ANDERSON, C.A., 1950. 1940 *E.W. Scripps* Cruise to the Gulf of California, Part I: geology of the islands and neighboring land areas. *Geological Society of America Memoir,* 43, 53p.

BERNER, R.A., 1989. Biogeochemical cycles of carbon and sulfur and their effect on atmospheric oxygen over Phanerozoic time. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 73, 97–122.

BISWAS, S.K., 1971. The miliolite rocks of Kutch and Kathiawar, western India. *Sedimentary Geology,* 5, 147–164.

BRAY, N.A., 1988. Thermohaline circulation in the Gulf of California. *Journal of Geophysical Research,* 93, 4993–5020.

BRAY, N.A. and ROBLES, J.M., 1991. Physical oceanography of the Gulf of California. *In*: DAUPHIN, J.P. and SIMONEIT, B.R.T. (eds.), The gulf and peninsular provinces of the Californias. *American Association Petroleum Geologists Memoir,* 47, 511–553.

BROOKE, B., 2001. The distribution of carbonate eolianite. *Earth-Science Reviews,* 55, 13–164.

BRUSCA, R.C., 1980. *Common Intertidal Invertebrates of the Gulf of California,* 2nd edition. Tucson, Arizona: University of Arizona Press, 513 p.

CARRANZA-EDWARDS, A.; BOCANEGRA-GARCIA, G; ROSALES-HOZ, L., and GALAN, L. DE P., 1998. Beach sands from Baja California Peninsula, Mexico. *Sedimentary Geology,* 119, 263–274.

CLARK III, G.R., 1974. Growth lines in invertebrate skeletons. *Annual Review of Earth and Planetary Sciences,* 2, 77–99.

EDWARDS, W.N., 1976. *The Early History of Palaeontology.* London, UK: British Museum (Natural History), 59 p.

FALKOWSKI, P.; SCHOLES, R.J.; BOYLE, E.; CANADELL, J.; CANFIELD, D.; ELSER, J.; GRUBER, N.; HIBBARD, K.; HOGBERG, P.; LINDER, S.; MACKENZIE, F.T.; MOORE III, P.; PEDERSEN, T.; ROSENTHAL, Y.; SEITZINGER, S.; SMETACEK, V., and STEFFEN, W., 2000. The global carbon cycle: a test of our knowledge of Earth as a system. *Science,* 290, 13 October, 291–296.

GOODWIN, D.H.; FLESSA, K.W.; SCHOÖNE, B.R., and DETTMAN, D.L., 2001. Cross-calibration of daily growth increments, stable isotope variation, and temperature in the Gulf of California bivalve mollusk *Chinoe* (*Chionista*) *cortezi*: implications for paleoenvironmental analysis. *Palaios,* 16, 415–426.

GOODWIN, D.H.; SCHÖNE, B.R., and DETTMAN, D.L., 2003. Resolution and fidelity of oxygen isotopes as paleotemperature proxies in bivalve mollusk shells: models and observations. *Palaios,* 18, 110–125.

GROSSMAN, E.L. and KU, T.L., 1986. Oxygen and carbon fractionation in biogenic aragonite: temperature effects. *Chemical Geology, Isotope Geoscience Section,* 59, 59–74.

HEARTY, P.J., 2003. Stratigraphy and timing of eolianite deposition on Rottnest Island, Western Australia. *Quaternary Research,* 60, 211–222.

HEDGES, J.I. and KEIL, R.G., 1995. Sedimentary organic matter preservation: an assessment and speculative thesis. *Marine Chemistry,* 49, 81–115.

HUNTER, R., 1993. An eolian facies in the Ste. Genevieve Limestone of southern Indiana. *In*: KEITH, B.D. and ZUPPANN, C.W. (eds.), Mississippian oolites and modern analogs. *American Association Petroleum Geologists Studies in Geology,* 35, 31–48.

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IVES, R.L., 1959. Shell dunes of the Sonoran shore. *American Journal of Science,* 257, 449–457.

JOHNSON, M.E., 2002. *Discovering the Geology of Baja California: Six Hikes on the Southern Gulf Coast.* Tucson, Arizona; University of Arizona Press, 221 p.

JOHNSON, M.E. and LEDESMA-VÁZQUEZ, J., 2001. Pliocene–Pleistocene rocky shorelines trace coastal development of Bahía Concepción, gulf coast of Baja California Sur (Mexico). *Palaeogeography, Palaeoclimatology, Palaeoecology,* 166, 65–88.

KEEN, A.M., 1971. *Sea Shells of Tropical West America* 2nd edition. Stanford, California: Stanford University Press, 1064 p.

MATTOX, R.B., 1955. Eolian shape-sorting. *Journal of Sedimentary Petrology,* 25, 111–114.

MCKEE, E.D. and WARD, W.C., 1983. Eolian environment. *In*: SCHOLLE, P.A.; BEDOUT, D.G., and MOORE, C.H. (eds.), *Carbonate Depositional Environments. American Association Petroleum Geologists Memoir.* Volume 43. Tulsa, Oklahoma; American Association of Petroleum Geologists, pp. 132–169.

MURRAY-WALLACE, C.V.; BROOKE, B.P.; CANN, J.; BELPERIO, A.P., and BOURMAN, R., 2001. Whole rock aminostratigraphly of the Coorong coastal plain, South Australia: towards a 1 million year record of sea-level highstands. *Journal of the Geological Society of London,* 158, 111–124.

OLSON, J.S.; GARRELS, R.M.; BERNER, R.A.; ARMENTANO, T.V.; DYER, M.I., and TAALON, D.H., 1985. The natural carbon cycle. *In*: TRABALKA, J.R. (ed.), *Atmospheric Carbon Dioxide and the Global Carbon Cycle.* Washington, DC: U.S. Department of Energy, pp. 175–213.

RICE, J.A. and LOOPE, D.B., 1991. Wind-reworked carbonates, Permo–Pennsylvanian of Arizona and Nevada. *Geological Society of America Bulletin,* 103, 254–267.

ROBERTS, N.C., 1989. *Baja California Plant Field Guide.* La Jolla, California: Natural History Publishing Company, 309 p.

RODEN, G.I., 1964. Oceanographic aspects of Gulf of California. *In*: VAN ANDEL, T.H. and SHOR, G.G. (eds.), Marine geology of the Gulf of California. *American Association Petroleum Geologists Memoir,* 3, 30–58.

RUSSELL, P. and JOHNSON, M.E., 2000. Influence of seasonal winds on coastal carbonate dunes from the Recent and Plio-Pleistocene at Punta Chivato (Baja California Sur, Mexico). *Journal of Coastal Research,* 16, 709–723.

SHEPARD, F.P., 1950. 1940 *E.W. Scripps* cruise to the Gulf of California, Part III: submarine topography of the Gulf of California. *Geological Society of America Memoir,* 43, 32 p.

SMITH, L.B., JR. and READ, J.F., 1999. Application of high-resolution sequence stratigraphy to tidally influenced Upper Mississippian carbonates, Illinois Basin. *In*: HARRIS, P.M.; SALLER, A.H., and SIMO, J.A. (eds.), Advances in carbonate sequence stratigraphy; application to reservoirs, outcrops and models. *Society for Sedimentary Geology Special Publication,* 63, 107–126.

THOMAS, D.S.G., 1997. Sand seas and aeolian bedforms. *In*: Thomas, D.S.G. (ed.), *Arid Zone Geomorphology: Process, Form and Change in Drylands,* 2nd edition. Chichester, UK: John Wiley and Sons, pp. 373–412.

VAN DER PLAS, L. and TOBI, A.C., 1965. A card for judging the reliability of point counting results. *American Journal of Science,* 263, 87–90.

VILLALEJO-FUERTE, M.; ARELLANO-MARTÍNEZ, M.; CEBALLOS-VÁZQUES, B.P., and GARCÍA-DOMÍNGUEZ, F., 1999. Reproductive cycle of chocolata clam *Megapitaria squalida* (Sowerby, 1835) (Bivalvia: Veneridae) in Bahía Jancalito, Gulf of California. Abstracts from VII National Congress and I International Symposium on the Sea of Cortés held May 26–28, 1999, in Cabo San Lucas, Baja California Sur, Mexico (Asociación de investigadores del Mar de Cortés), p. 27.

WILLIAMS, G., 1964. Some aspects of eolian saltation load. *Sedimentology,* 3, 257–287.

ZEITZSCHEL, B., 1969. Primary productivity in the Gulf of California. *Marine Biology,* 3, 201–207.

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