Reports

Anaerobiosis in Marine Sandy Beaches

Abstract. Organisms living at depths greater than 5 to 10 cm in marine beaches composed of fine sand are completely anaerobic whenever their particular section of beach is covered by water. Anaerobic conditions are continuous if the slope of the beach is slight enough so that capillary forces keep the sand saturated with water even at low tide.

The water in the spaces between the sand grains of beaches supports an abundant and varied flora and fauna. In marine beaches, bacteria of a wide range of types are present in numbers varying from at least several thousand to several million per gram of sand in the surface layers between tide marks. There tends to be a decrease in numbers as the low tide line is approached and as one goes down into the sand. There is also a decrease in the proportion of aerobic forms with depth (*1, 2*). Diatoms and various other algae are often numerous, with diatom numbers ranging up to at least 20,000 per cubic centimeter of sand. Living algal cells commonly occur to depths of 8 to 10 cm, but photosynthesis and growth are restricted by the lack of light to the upper centimeter or less (*1, 3*). A wide variety of unicellular and metazoan animals also occurs. Microscopic forms are common to depths greater than 40 cm and are more abundant than macroscopic types. Many hundreds of species of such "psammophile" animals have been described from beaches in various parts of the world. Nematodes probably are the most abundant and varied group (*1, 3, 4*).

The physical and chemical environment in which these organisms exist is a rigorous one in many ways. Several studies have shown that perhaps the most stringent condition imposed is that of oxygen shortage, if not complete lack of oxygen, for extended periods. The present study was undertaken both to check the small number of direct observations of interstitial oxygen concentrations reported previously (*1, 5*) and to find out more about the duration of periods of oxygen shortage experienced by the flora and fauna of the sand.

Interstitial oxygen concentrations were measured to depths up to 20 cm in four beaches in various parts of Southern California and Baja California. None of these beaches were polluted as a result of human activities. The study areas on the four beaches differed considerably in the size distribution of particles in the surface sand (Table 1). Beach slopes ranged from $< 1°$ above horizontal at Rincon to 6° at Corona del Mar. The coarse-sand beach at Gonzaga Bay was underlain by a rough layer of solid rock at a depth of about 10 cm; the other, finer-sand beaches all had sand layers at least several feet thick. Surf action was nil to light during the study periods at all beaches. Measurements during both falling and rising tides were made only at Gonzaga Bay and Corona del Mar.

Subsurface water samples free of visible debris were obtained completely without contact with the air by suction into 5 or 10 cm^3 glass hypodermic syringes. At Gonzaga Bay long hypodermic needles were simply inserted into the sand to the desired depths. At the other beaches a sampler was used which consisted of a length of transparent plastic tube marked off in centimeters. This was fitted with an ordinary aquarium air-bubbler stone as a filter at the lower end and a standard hypodermic needle base attached to the outlet side of a small, airtight brass line valve at the upper end. Series of samples were taken at each location, from an initial depth of 20 cm and at 5-cm intervals from that point to the surface. At each depth, sampler and syringe were flushed several times with the interstitial water from that depth. Calculations based on the volume of water flushed through the sampler at each point indicate that a sphere of about 3 cm radius was sampled. Samples for analysis were stored in the syringes in which they were taken. The syringes were sealed from the air by tightly fitting glass rods inserted, without any bubble entrapment, into short lengths of Tygon tubing fitted over the syringe nozzles.

Oxygen analyses were carried out with the method and apparatus of Scholander *et al.* (*6*). One-cubic-centimeter aliquots of the water samples were analyzed within 6 hours of collection. Duplicate analyses run within a few minutes agreed within 1 to 2 percent. Duplicate analyses of samples stored for periods of 24 hours showed less than 10 percent decrease in oxygen content due to respiration of contained bacteria and other microscopic organisms.

Regardless of tidal stage, as long as the spaces between the sand grains were filled with water, all the beaches studied showed markedly lower oxygen concentrations in the interstitial water than in the surface sea water. The rapidity of the decrease in oxygen content with increase in depth varied with particle size distribution.

At Gonzaga Bay, surface water concentrations ranged between 5.5 and 7.0 cm^3/lit. (5 samples), while samples from 10 cm into the beach (the deepest obtainable due to the underlying rock layer) varied from 2.0 to 6.0 cm^3/lit. (14 samples). No consistent pattern of variation of interstitial oxygen con-

Table 1. Weight percentages of particle size classes in mechanically sieved single samples of surface sand from beach study in the following areas: north shore, San Luis Gonzaga Bay; cove, south shore, Punta Banda; Rincon, just north of Punta Banda; county beach, Corona del Mar.

Sand grain diameter (mm)	Baja California, Mexico, 1959			Corona del Mar, Calif. 28 Dec. 1959, 2 Jan. 1960
	Gonzaga Bay 29 Jan.–3 Feb.	Punta Banda 23 June	Rincon 24–25 June	
> 4.0	0.7	0.0	0.0	0.0
4.0 –2.0	1.6	0.0	0.0	0.0
2.0 –1.0	3.5	0.5	0.0	0.5
1.0 –0.50	82.8	2.1	0.4	3.4
0.50–0.25	6.7	4.4	0.6	19.5
0.25–0.12	4.0	87.7	8.6	65.6
0.12–0.062	0.5	4.8	41.6	10.3
< 0.062	0.2	0.5	48.8	0.7

Instructions for preparing reports. Begin the report with an abstract of from 45 to 55 words. The abstract should *not* repeat phrases employed in the title. It should work with the title to give the reader a summary of the results presented in the report proper.

Type manuscripts double-spaced and submit one ribbon copy and one carbon copy.

Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each.

For further details see "Suggestions to Contributors" [*Science* **125**, 16 (1957)].

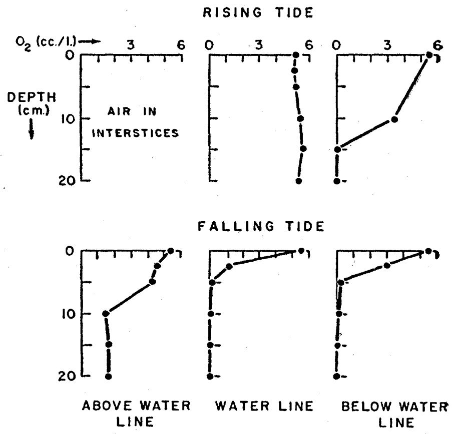

Fig. 1. Interstitial oxygen concentrations in the beach at Corona del Mar during both rising and falling tides. Sampling sites 3 to 5 m apart horizontally normal to the surf line. "Above water line," highest area on the beach reached by wash of breaking waves at time of sampling; "water line," area on the beach covered by wash of breaking waves about 50 percent of the time of sampling; "below water line," lowest area on the beach exposed to the air by the receding wash of breaking waves at time of sampling.

centration with respect to position on the beach relative to water level on either falling or rising tides could be determined at Gonzaga Bay. The lowest concentration measured was 0.4 cm^3/lit. at a depth of 3 cm at the water line on a falling tide. Pockets of relatively stagnant water retained in depressions in the surface of the underlying rock layer probably account for the variability of results here.

Surface water in the cove on the south shore of Punta Banda had 5.4 to 5.5 cm^3 of oxygen per liter (2 samples). Interstitial oxygen 3 to 5 cm into the beach at the water line on a falling tide was 0.9 to 1.4 cm^3/lit. (4 samples taken within 20 cm of one another).

Surface water at Rincon had 4.8 to 4.9 cm^3 of oxygen per liter (2 samples). The beach here is flat, and the sand is fine, so that capillary forces keep the interstices between the sand grains filled with water even near the high-tide line at low water. Two sets of duplicate samples from two places on the beach about 1 mile apart, both sets taken somewhat above midtide level just before the rising tide covered the sampling spots, showed 0.5 to 0.6 cm^3/lit. at 2 to 3 cm, 0.1 to 0.2 cm^3/lit. at 5 to 7 cm, and 0.0 to 0.1 cm^3/lit. at 10 to 12 cm. The sand was black and gave off an odor of H_2S below about 12 cm.

The more complete study of the beach at Corona del Mar demonstrates another point in addition to the occurrence of anaerobiosis (Fig. 1). This is that whatever oxygen enters the beach disappears rapidly. All observations were made in an area about 5 cm long at about the two-thirds tide level on the beach. Independent series of analyses were made on two different days for each situation. Single samples were taken from each depth in each series. Points plotted in Fig. 1 are means for the replicated series, which averaged agreement within 0.3 cm^3/lit. for samples from depths of 5 cm or more. In each situation air-saturated water percolated into the beach from the waves washing up on its surface. On the rising tide, when the interstices were full of air to start with, percolation was very rapid. This resulted in uniform oxygen saturation of the water filling the interstices, at least down to 20 cm. This oxygen was completely gone, however, at depths of 15 cm and more, within 15 to 20 minutes (the time required for the water line to move up the beach the distance between the "below water line" and "water line" sites).

The situation on the falling tide was even more extreme, anaerobiosis occurring at 5 cm at and below the water line. Part, at least, of the rapid drop in oxygen concentrations between the "above water line" and "water line" sites in this situation was due to slowing of percolation of surface water by the anaerobic water already present between the sand grains.

Some, but not all, of the samples from 10 cm or more into the beaches contained larger quantities of dissolved inert gases (N_2,Ar, perhaps CH_4) than did surface water samples.

The organisms inhabiting fine-grained intertidal sandy beaches at depths greater than 5 to 10 cm must, therefore, be capable of surviving periods of complete anaerobiosis which are very nearly equal in duration to the periods when these particular portions of the beach are submerged by the tide. If the beach involved is very fine-grained, with little slope, anaerobic conditions may be continuous. Organisms living in sands below low tide line are almost surely continuously anaerobic.

The biochemical and physiological adaptations which allow metazoan animals to survive under these extreme conditions must be very striking. The existence of such adaptations is strongly indicated by the fact that several types of sand-dwelling mollusks and nematodes can survive complete anaerobiosis in the laboratory for periods of months and that many other forms survive up to at least 1 week (*7, 8*).

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References and Notes

A. S. Pearse, H. J. Humm, G. W. Wharton, *Ecol. Monographs* **12**, 135 (1942).
2. J. Senez, *Ann. inst. Pasteur* **77**, 512 (1949); *Année biol.* **27**, 425 (1951).
3. R. W. Pennak, *Année Biol.* **27**, 449 (1951).
W. Wieser, *Limnol. Oceanog.* **4**, 181 (1959); *Free-Living Nematodes and Other Small Invertebrates of Puget Sound Beaches* (Univ. of Washington Press, Seattle, 1959).
5. M. A. Borden, *J. Marine Biol. Assoc. United Kingdom* **17**, 709 (1931); R. W. Pennak, *Ecology* **23**, 446 (1942).
6. P. F. Scholander, L. van Dam, C. L. Claff, J. W. Kanwisher, *Biol. Bull.* **109**, 328 (1955).
7. T. von Brand, *Biodynamica* **4**, 185 (1944); H. B. Moore, *J. Marine Biol. Assoc. United Kingdom* **17**, 325 (1931).

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Sequential Deoxyribonucleic Acid Replication

The deoxyribonucleic acid (DNA)–synthesizing system of Kornberg and co-workers (*1*) provides a basis for refinement of the commonly held mechanical schemata of DNA replication. Diagrams to illustrate replication of the Watson-Crick structure generally show the simultaneous formation of two double structures at each growing point, as in Fig. 1. Since the unfinished chains are antiparallel, such diagrams require that the chains grow by different mechanisms: one by addition to the 3′-

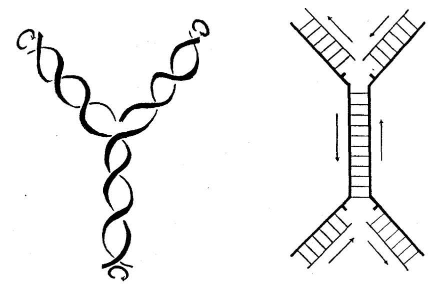

Fig. 1. Replication of Watson-Crick structure, showing simultaneous formation of two double structures at each growing point.

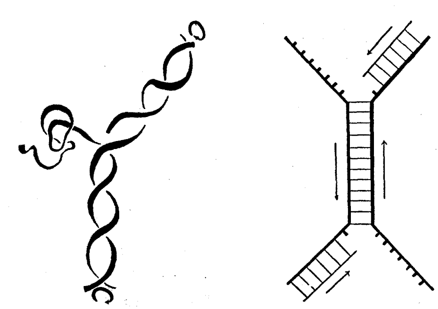

Fig. 2. Undirectional growth of DNA chain, showing sequential (left) and semi-sequential (right) growth.