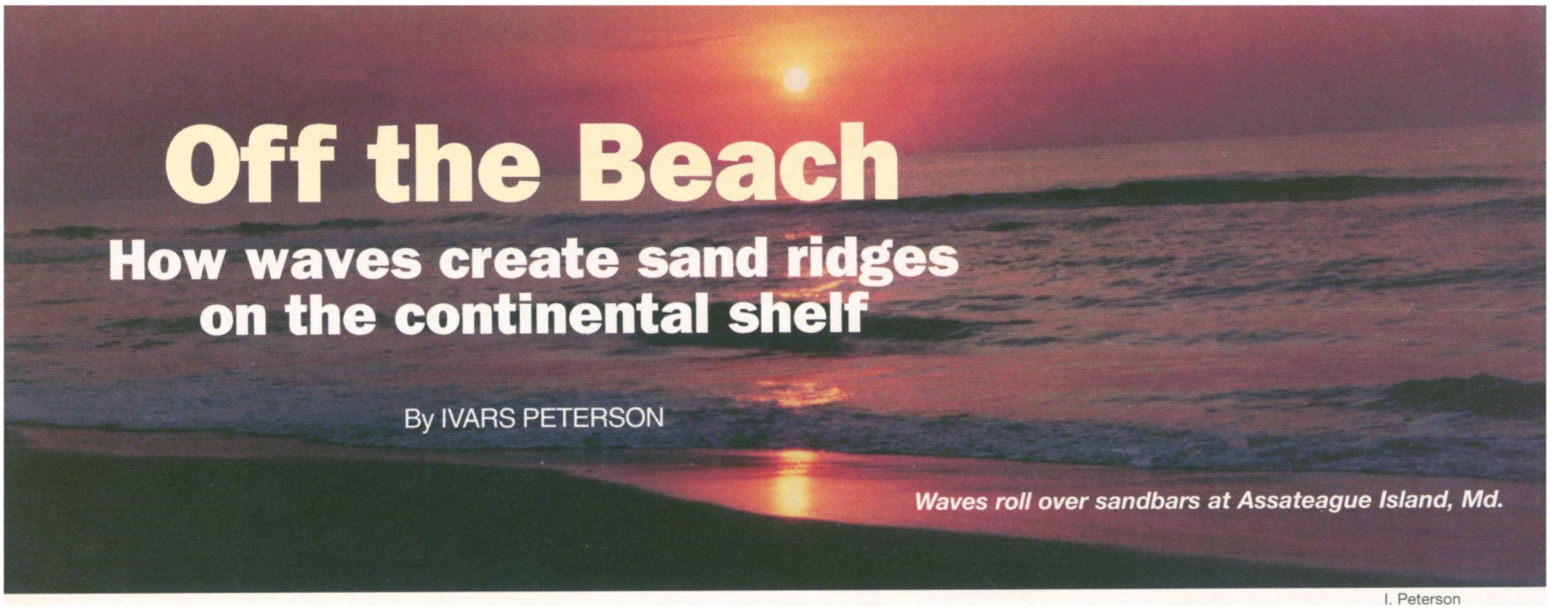


Off the Beach

How waves create sand ridges on the continental shelf

By IVARS PETERSON

Waves roll over sandbars at Assateague Island, Md.

I. Peterson

When I was a child, my family occasionally vacationed at Wasaga Beach—a 9-mile-long strip of sand cradled in the Georgian Bay arm of Lake Huron. One of my more vivid memories of those days at the beach is of wading out a long distance from shore, following the undulations of the gently sloped, sandy bottom.

What made these ventures particularly appealing was a sequence of underwater sandbars running roughly parallel to the shore. Instead of increasing steadily, the water depth would rise and fall as I traversed these ridges. Sufficiently far out into the bay, it was possible to descend into a broad hollow and come thrillingly close to being swamped by waves before reaching the shallows of the next sandbar in the sequence.

Many other beaches throughout the world display similar sandbar patterns near shore. But the most striking examples of such arrays occur on the sandy ocean floor of the continental shelf.

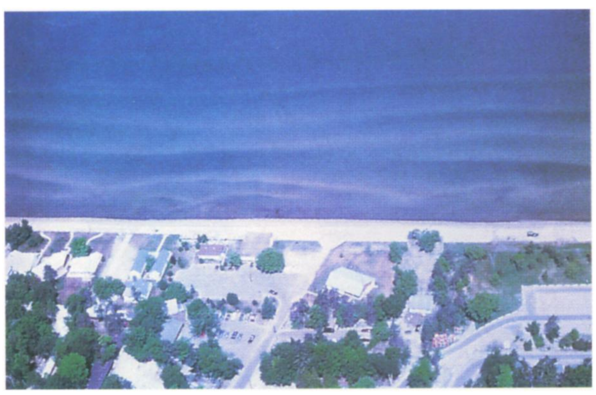
There, one can find vast fields of sand ripples, arranged by the dozens in neat,parallel rows. Each ridge rises to a height of a few meters and stretches hundreds of meters in length. Maintaining a separation of a few hundred meters, these crests gradually shift their positions,slowly creeping as a group across the ocean bottom.

What causes such distinctive patterns to form wherever sand is abundant near shore or on the continental shelf? Why do some sets of ridges move or change shape? What makes some of them remain stable overlong periods of time while others quickly appear, then disappear?

Over the years, oceanographers and geologists have offered a number of explanations for these surprisingly regular features, ranging from tidal or ocean current effects to wave action due to storms. But these models generally fail to account for all of the key features of sand ridges.

"The dynamics of [underwater] sand ridges are not well understood," say applied mathematicians Juan M. Restrepo of the Argonne (Ill.) National Laboratory and Jerry L. Bona of Pennsylvania State University in University Park, who have developed a novel mathematical approach to modeling the interactions between waves and sandy seabed.

In a paper to be published in the mathematics journal NONLINEARITY, Restrepo and Bona suggest that certain types of ocean waves—those with large amplitude and long wavelength—are largely responsible for the formation of these seabed structures. These prevailing waves ruffle the ocean surface and create corresponding- movements in the water at the seabed; these motions scoop sand out of one place and pile it up in another.



Boczar-Karakiewicz

Aerial view of sandbars running roughly parallel to the shore of Lake Huron.

Though the arrays of underwater ridges that appear off many coasts probably owe their existence to a number of causes, the seabed water flow induced by wave action contributes significantly to the generation and evolution of these structures, the researchers contend.

This model not only produces sandbars of the right size and shape but also makes predictions that are testable in the laboratory or field.

"Our model predicts that it's a slow, gradual process," Restrepo says. "But this conjecture has not yet been checked out in the ocean environment."

Models of how sand drifts from place to place offshore are useful to coastal engineers and others interested in stabilizing shorelines and preventing beach erosion, biologists concerned with the movement of nutrients along the ocean bottom, and geologists prospecting for trace metals, which tend to accumulate in sandbars.

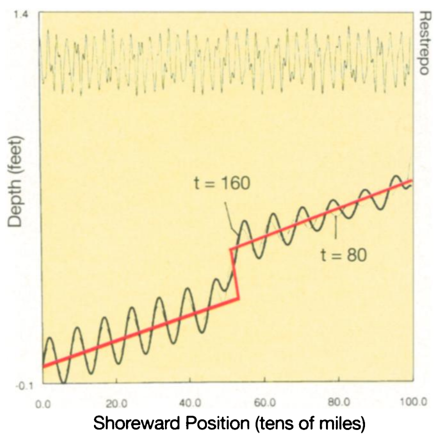
A specialist in fluid dynamics, Bona first learned of seabed sand ridges more than a decade ago, when he met Polish oceanographer Barbara Boczar-Karakiewicz, now at the University of Quebec in Rimouski. Her descriptions of huge fields of regularly spaced sand ridges in the Baltic Sea and elsewhere intrigued him.

Boczar-Karakiewicz had measured the dimensions and other characteristics of a number of these seabed structures. Collaborating with experts in fluid mechanics, she had set up exploratory experiments in large water tanks to test some of her ideas concerning the origin of these features. Early on, she suspected that certain wave characteristics might account for the formation of these sandbar patterns.

Working with several graduate students, Bona began developing a mathematical model describing how waves interact with particles of sand on the ocean floor. "We wanted to mimic the formation of these structures mathematically," Bona says.

He also spent time in the laboratory collaborating with colleagues studying how waves travel through water, particularly the subsidiary movements that wave action induces within the liquid and near its interface with the bottom. The researchers identified a particular type of fluid behavior associated with certain components of large ocean waves as the potentially critical factor shaping the ocean floor.

Ordinarily, in the case of sound waves or the tiniest water ripples, there's no net movement of the air or water as the



Computer simulations demonstrate how a smooth slope with one kink (red line) can wrinkle into a sequence of sand ridges (bottom curves) after the passage of many surface waves (top curve).

wave propagates through it. Particles of the medium circulate about their original positions. In contrast, for the typical kinds of waves that traverse coastal waters,each little volume of water, including those in the sediment-laden layer hugging the ocean bottom, ends up moving a short distance in the direction in which the wave travels.

For sand ridges, which form in areas of the ocean where waves rarely break, it's the resulting "boundary layer drift velocity" that's responsible for sediment movement, Bona and Restrepo say.

Striking similarities between the direction and wavelength of the strongest, most regular components of ocean waves in a given region and the typical ridge spacing and orientation of seabed structures in the same area lend support to this idea, the researchers add.

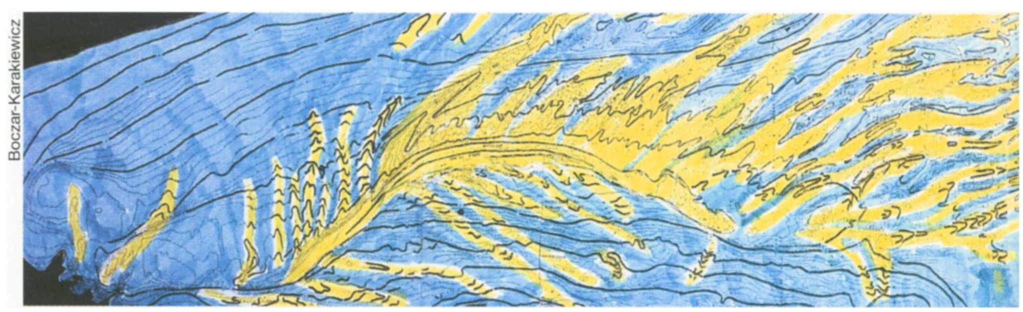
But it's no simple matter to solve the hydrodynamic equations describing these waves. Researchers must use simplified versions of the equations and powerful computers to obtain answers and make predictions about wave behavior. Bona and his coworkers started with an extremely crude wave model and over the years gradually refined it, extending it from two to three dimensions, adopting more realistic descriptions of the ocean waves, and adding other effects. In its present form, their model combines a mass transport equation, which controls the history of the bottom topography, with an equation describing the evolution of the most energetic, coherent components of the surface waves.

Computer simulations show that sufficiently strong swells obeying these rules can create the coherent, organized flows needed to stir a sandy ocean bottom into sets of evenly spaced ridges of the requisite dimensions.

Gradually, as wave after wave passes over a sandy bed, the flat or slightly sloped bottom becomes increasingly rumpled. The resulting ridges, in turn, affect the waves, changing their motion slightly. The net result is a sandbar pattern whose characteristics depend on the amplitude and wavelength of the surface waves and the slope of the bottom.

"The pattern that forms on the bottom has a structure that is inherited from the ocean waves," Restrepo says.

Comparisons with the limited amount of field data now available have proved encouraging. "That doesn't mean we're right, but we seem to have captured the gist of what's going on," Bona says. "This gives us some confidence in our model."



Contour map showing an orderly field of sand ridges in the Sable Island Bank off the coast of Nova Scotia.

The argument that the drift velocity originating in long-wavelength ocean waves is enough to move sand into the observed patterns has proved controversial. A number of oceanographers have argued that the energy associated with this secondary flow is insufficient to move the quantities of sediment needed to create oceanic sand ridges.

Several have pointed out that violent storms may play the predominant role in creating these features. But that's an unsatisfactory explanation, Restrepo says. How does the apparent disorder of an intense storm create such a high degree of order? he asks.

In the Bona-Restrepo approach, the sandbar patterns develop slowly, over months or years. Most other models focus on rapid formation, neglecting the subsequent evolution of the pattern.

Other critics have noted that a number of different mechanisms may be involved, especially in creating sandbar patterns at beaches, where incoming waves interact with reflected waves. Bona concedes that several factors may contribute to the formation of sand ridges in different locations at different times.

Further tests of the Bona-Restrepo model require additional field data, including accurate measurements of both the bottom topography and the full spectrum of amplitudes and wavelengths of surface waves in the same vicinity.

"But the task of making the necessary field observations is a tedious, expensive, difficult enterprise," Restrepo and Bona point out.

Laboratory experiments may provide some of the answers, although it's difficult to get waves and particles of the right scale to match ocean conditions. Nonetheless, researchers can try to measure the pattern of wave-induced drift velocities in different settings.

"I want to look at the velocity distribution [within the water] to make sure that it has the properties that we think should be evident in a sandbar field," Restrepo says.

Restrepo is also interested in determining experimentally whether sand ridges develop and evolve slowly and smoothly or in short spurts. "This is a key question," he says. "If the latter is true, our model is incorrect, and so are a vast number of other models."

The research remains far from complete. "We're working on a number of theoretical issues," Bona notes. "And we're refining the model further."

The researchers are taking a closer look at the mathematical structure of the equations used to model waves and defining more precisely the types of seabed environments where the equations- are most likely to apply.

"We're also trying to answer the question of what are the stable and unstable [sandbar] configurations, another key oceanographic question," Restrepo says.

Overall, the efforts of Bona, Restrepo, Boczar-Karakiewicz, and others represent just one facet of an ongoing effort to understand the complex, varied structures observed on the ocean floor.

"Any topographical chart of the continental shelf provides a good reminder of the long path [we have] yet to travel toward a complete understanding and model of the full problem," Bona and Restrepo conclude. □