REORIENTATION OF CONVEX SHORES

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ABSTRACT. Convex shores are commonly marked by downdrift decreases in energy. These decreases are due to wave refraction. Shores of this type develop an equilibrium outline by a combination of updrift erosion and downdrift deposition. The resulting form is a concavity or embayment having a radius of curvature equal to about one-fourth of the effective fetch. Several such concavities, with their intervening spits and shoals, may give the shore a “scalloped” look; bays and lagoons having shores shaped in this fashion have been described as “segmented”. The oval marshes known as the “Carolina Bays” formerly may have been lakes that were given their nearly circular outlines in the same way. Not all coastal concavities are due to this process, however, and not all equilibrium shores have the scalloped outline.

INTRODUCTION

The curvature and sand prism characteristics of the equilibrium beach are adjusted to each other so delicately that the potential littoral motion provides precisely the energy needed to transport the detritus supplied at the up-current end; the time element in this balance is long term rather than instantaneous (Tanner, 1958, 1960b).

Many beaches depart from this ideal. If the departure is violent or marked, the beach can be characterized as in nonequilibrium. If the departure is slow or subtle, the beach may be said to have a shifting equilibrium. A shifting beach may be prograded (advancing toward the sea) or retrograded (retreating toward the land).

Along a given stretch of beach, conditions need not be constant from point to point, for energy level or littoral drift load, or both, may vary. Drift load can be added (for example, by streams), or lost (for example, seaward across the continental shelf, particularly where the latter is narrow and steep). Energy levels can be altered in several ways. It is the purpose of this note to examine one of these ways, and to list a few pertinent examples.

ENERGY LOSS

Several mechanisms may reduce the energy along a given stretch of beach. Some of these are:

1. Shoaling (that is, a reduction, along the coast, of the bottom slope, so that the updrift portion is steeper than the downdrift portion).
2. Protection of part of the coast by an offshore island.
3. Refraction of the wave pattern around a headland or curve (Kuenen, 1950, p. 82).
4. Wave decay.

Each of these should be relatively easy to identify, either on charts or in the field, except for the unimportant fourth case. Identification of the first one requires that water depths be known. The second needs no additional comment. The third should be obvious, provided the coastal outline and the direction of dominant wave attack are known.

In the third case, the energy available on a unit width of beach front (under given wave conditions) is roughly proportional to the product of the
maximum energy delivered at any unit on the curve, and the cosine of the angle between the tangents to the beach at the two points in question. In other words, wave energy around a curve decreases with the cosine. Where the beach deviates by $10^\circ$ from its updrift orientation, the energy is reduced by a factor 0.9848 (provided the updrift end of the beach was subject to head-on wave attack). For a $20^\circ$ deviation, the factor is 0.09397. These figures apply to a beach having a convex plan.

Convex beaches are fairly common, particularly in lagoons. The convex curvature develops on the protected side of the barrier island, the seaward side of which is gently concave. Littoral drifting in either direction along the convex beach is complicated by the energy reduction. Degree of curvature of convex beaches is highly variable, but values in the low to middle tens of degrees are common. Hence maximum potential wave energy might be reduced from one end to the other, to some value perhaps between 50 percent and 90 percent of the original. This reduction will be altered, in part, by the increased fetch. The total alteration cannot be stated in simple rigorous terms for all cases, but can be computed fairly easily in each instance and in general will be small.

Reduction of energy down the length of a beach generally results in deposition of drift load. This deposition may be realized in several different ways. The downdrift portions of the beach may shift seaward, the excess sand may be blown inland to form a dune field, or one or more shoals may form near the shore. One, two, or all three of these features may develop simultaneously.

The large shoals on the Atlantic coast of North Carolina (off Cape Hatteras, Cape Lookout, and Cape Fear [Tanner, 1960a, 1961] are good examples. The shoal south of Cape Romano, Florida is of the same type. (The shoals off Cape St. George and Cape San Blas, in the panhandle of Florida, have formed despite an increase of energy along the coast; they exist because of delivery of a relatively large load of sand and silt by the Apalachicola River.)

**BEACH CURVATURE**

A similar mechanism may operate along beaches which are not convex. Ideally, energy levels should increase down a straight beach, primarily because

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**Fig. 1.** Diagram showing how a combination of updrift erosion and downdrift deposition (of the same material) can lead to a concavity or embayment in the shoreline. The diagram represents a constant-energy, perfectly straight, infinitely long coast. Under such conditions, the excess of material eroded, over material deposited, is transferred to infinity. In nature, coasts are limited in length, commonly not straight, and variable in energy levels. Under such conditions, excess eroded material will be deposited somewhere in the downdrift direction, resulting in a spit or point which grows seaward. Distance of littoral displacement in the diagram: 2 units.
of the increased fetch (barring the special, temporary conditions where wave decay may occur). This lengthwise increase in energy does not mean, however, that all points of the beach will be cut back equally or uniformly. Sand moves, for any given set of wind conditions, only a short distance along the beach before coming to rest again.

If the drift materials could be whisked away, by pushbutton magic, as the wind-waves begin to die down, the new strandline would look something like one-half of a parabola, with the vertex located at the point where the waves first became effective (fig. 1). Drift materials are not whisked away in nature, however. If average grain motion in the drift is two miles, then a "curve of deposition" must be added to the "curve of erosion", but the former, although enclosing an area equal to the latter, must be shifted two miles in the down-drift direction. For this reason, the strandline which appears after the waves die down is neither the original line nor the line due to erosion only. Instead it is a sinusoidal curve having one rather obvious node close to the updrift end of the beach. This node is a concavity.

If the beach were straight and infinitely long, and energy conditions were constant within the limitation set by fetch, there should be no point at which deposition exceeded prior erosion. That is, there should be no point at which the "curve of deposition" protruded farther into the water than the original strandline. The net loss of material, from the new-formed concavity, would be transferred "to infinity", and the recession of this portion of the beach would not be offset by an advance, seaward, at any point.

However, beaches are neither infinitely long nor perfectly straight. On curved or limited coasts, the amount of material removed in the updrift concavity must be equalled, when calm conditions return, by the amount deposited farther down the beach.

Therefore, even on a straight coast, the updrift end of the beach should undergo erosion. Farther down the beach net deposition should occur. The result should be rotation of the strandline about a "fulcrum" somewhere between the two stretches. The new orientation of the beach will be a bit closer to perpendicular to unrefracted wave attack. In due time, provided nothing interferes with the process, a complete reorientation may be achieved, as Lewis (1938) and Schou (1952) have shown.

The point of maximum net erosion tends to be close to the updrift end of the beach. Its precise location is affected by at least four factors. These are:

1. The linear distance over which the drift is moved during an average period of transport (that is, before calm conditions return). If the average distance is short (such as a few meters), the point of maximum net erosion will tend to be very close to the updrift end. If the average distance is great (such as a few miles), the point of maximum erosion will tend to be much farther down the beach from the updrift end.

2. The ratio between the fetch at the downdrift end and the fetch at the updrift end. If these two values are greatly different (i.e., \( f_d/f_u = 2 \)), the point of maximum net erosion will tend to be sharply defined, and near the updrift end of the beach. If the ratio is close to one, the maximum net erosion will occur over a larger area and will be centered farther down the coast from the
updrift end. Hence in lagoons and lakes we may expect relatively sharp curvature, whereas along the open ocean more gentle curves should be expected.

3. Long-term uninterrupted duration of the process. Continuous operation of the mechanism here described may tend to move the point of maximum net erosion down the beach, away from the updrift end.

4. Average energy level for the coast. An increase in this factor appears to produce the same result as prolonged continuous operation.

The above discussion has been based on a study of an ideal straight coast supplied with ample sand. Where the coast is convex seaward, the downshore reduction in energy requires a net downshore decrease in the drift load, and hence greater deposition than in the straight-beach model. The result should be a sharpening and lengthening of the arc of curvature.

Hoyle and King (1958) postulated an equilibrium arc for beaches. The figure they gave was close to 14°. Curvature of about two dozen stretches of mobile coast have been examined in the course of the present study. None had arcs anywhere near as small as 14°. Two general categories have been observed: those facing the open ocean (unlimited fetch) have large radii of curvature (tens of miles) and subtend about 50°. Those developed along lagoons (greatly reduced fetch) have small radii of curvature (smaller than 10 miles) and subtend 90° or more.

Although the data are as yet too meager to permit precise statements, it appears that fetch is equal to about four times the radius of curvature.

SEGMENTED BAYS

Nantucket Harbor (Nantucket County, Massachusetts; fig. 2) is about six miles long and one mile wide (Jones and Lucke, 1951). The northwestern shore is convex (it is the back side of a concave beach ridge complex which faces Nantucket Sound). Maximum fetch can be obtained in either a northeasterly or southwesterly direction; resulting waves will be refracted around the curvature provided by the convex strand. The fetch ratio (see Beach Curvature, §2, above) falls between two and five. Wave erosion should produce concavities (embayments) having small radii and subtending large arcs. Fetch varies between one and six miles; the radius of curvature should be about one-fourth of the fetch, or 0.25 to 1.50 miles. The arcs subtended should be as large as 90° or larger. The average measured radius of curvature is 0.57 miles; the minimum is about 0.50 miles, the maximum about 0.68 miles. The average arc subtended is 120°, the minimum about 110°, the maximum about 140°.

The lagoons in the vicinity of Cape Canaveral (Brevard County, Florida) are approximately two miles wide and more than 10 miles long. The eastern shores are convex (backs of barrier islands between the lagoon and the Atlantic Ocean). Concavities on these convex shores typically have radii of about one mile, and subtend arcs of 90° to 100°.

On the curved barrier island in Okaloosa County, Florida, concavities have developed on the convex shore of the lagoon. A typical radius is two miles, subtended arc about 90°.

The Nantucket embayments appear to be representative of those studied. Five concavities are well developed on the northwest side of Nantucket Harbor,
and a possible sixth may be found at the northeast end. Remnants of old beach ridges on the spit between the harbor and Nantucket Sound (to the northwest; fig. 2) permit a tentative discrimination between eroded and deposited portions of the harbor shore. The old beach ridge complex has been cut out, normal to the strand, for a distance which reaches an average maximum of between 500 and 800 feet. Between the embayments, spits extend approximately 1000 feet, each, in a southeasterly direction, into the waters of the harbor. Shoals more than 1000 feet long extend even beyond the tips of the spits. The orientation of the shoals indicates that the waves which were effective in shaping this stretch of shore traveled out of the south or southwest. Generalized wind data for the area show westerly winds, averaging 8 to 13 miles per hour, in the fall, winter, and spring, and southwesterly winds averaging about 8 miles per hour in the summer. The westerly winds are land breezes for this stretch of beach; the southwesterly winds are probably responsible for the shaping of the shore. The average fetch for these winds is about 2 miles. The embayments have smoothly curving beaches, which, when taken with the shoals, present a maximum strand length at right angles to the effective winds.

Most of the spits studied by the present writer were not paired with spits on the opposite shore. Where pairing was noted, it was thought that the effect was accidental and not due to the mechanism here suggested.

Cuspat spits similar to those described here have been discussed previously by Fisher (1955) and by Price and Wilson (1956). The latter two authors suggest that they may be due to standing-wave oscillations or seiches.

Fig. 2. Nantucket Harbor, Massachusetts, showing the alternation of embayments and spits on the convex northwestern shore. The southeastern edge of the old beach ridge complex permits recognition of eroded areas (concavities) and deposited features (spits and shoals).
SMALL LAKES

Completely enclosed bodies of water, located on mobile materials such as sand, should also respond to the reorientation here outlined. If the materials available are truly mobile, concavities should develop on each side. The material eroded from the sides should accumulate at the downwind end of the lake. The resulting shape should be almost circular or elliptical. Under such circumstances, the radius of curvature might approach the fetch, and the arc subtended on each side should be roughly 180°.

Where several such lakes are located close to each other, all might have the same general orientation. It is possible that the Carolina Bays (Melton and Schriefer, 1933; Cooke, 1954; Schriefer, 1955, 1956) were formerly lakes of this type, which have subsequently become marshes.

COASTS WITHOUT BAYS

Most of the shores of the world do not have the concavities described here. They are marked, instead, by either the irregularities of the nonequilibrium or subequilibrium conditions (Tanner, 1960b), or by the very great regularity of the ordinary equilibrium condition. The concavities off North Carolina (between the three Capes: Hatteras, Lookout, and Fear) appear to be due to a southward decrease in wave energy, which may be related to the general seaward convexity of the coast. Where the shore is concave seaward—as along the east coasts of Florida, Georgia, and Texas—a more or less stable equilibrium (or shifting equilibrium) may be present, and hence no reshaping of the map outline is necessary.

SUMMARY

Energy may be lost in a downdrift direction by several different mechanisms. An important method is by wave refraction around a convex (seaward) shore. Convex shores are common along lagoons, less common along the oceans.

Because, in restricted bodies of water, increases in wave energy with distance are sharp in the first few miles downwind from the onset of wave activity, and gradual beyond that point, even a straight shore may be reoriented by a combination of updrift erosion and downdrift deposition. Where this reorientation is combined with a downdrift energy loss due to refraction around a convex coast, typical embayments or concavities develop. Concavities of this type, separated by spits and offshore bars and shoals, produce "segmented" lagoons or bays.

In general, radius of curvature of these concavities appears to be roughly one-quarter of the fetch, up to the practical limit of fetch equal to about 300 miles. Arcs of curvature vary from about 180° for very small bodies of water (such as small lakes or ponds) to about 50° along the shores of the ocean.

Concavities of this type mark an equilibrium shoreline. If an ample supply of mobile material is present (such as sand), this equilibrium may be reached very quickly (perhaps in a few hundreds or at the most a few thousands of years). Provided no new complications are introduced, the scalloped form that results should be reasonably stable.

Not all strand concavities of the scale given here are due to this mechanism. The embayment between Cape St. George and Cape San Blas, in the
panhandle of Florida, is due to a local excess of drift load (near a river mouth),
despite an increase in energy levels along the shore.

Not all equilibrium beaches have the scalloped form here described.
Straight, convex, and faintly concave stretches of coast may be in either stable
or shifting equilibrium. A concave coast having a downdrift increase in energy
levels should, in general, develop a curvature determined more-or-less directly
by the energy-load relationship along the shore in question.

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