Carolina Bays and the Shapes of Eddies

By C. WYTHE COOKE

A SHORTER CONTRIBUTION TO GENERAL GEOLOGY

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Presenting corroborative evidence that the elliptical Carolina bays were shaped by tidal eddies and that the shape of the ideal eddy is elliptical

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By C. Wythe Cooke

ABSTRACT

All classes of matter have gyrostatic properties following the universal laws of motion. Liquids moving in a curved path react in the same way as solids, though the manifestation appears different because particles of a liquid are able to move independently of one another. So, if the plane of rotation of a liquid is tilted, the circular orbits of the particles are distorted into ellipses because the horizontal components of the centrifugal force vary in intensity according to the direction.

An eddy, like a spinning flywheel, resists any couple that tends to alter the direction of the axis of rotation. The application of such a couple causes the axis either to precess or to set its direction parallel to the axis about which it is forced to turn. The rotation of the earth is constantly turning the axis of rotation of an eddy out of its initial direction in space. Consequently, the axis of rotation of the eddy either precesses about the horizontal east-west diameter of the eddy or the axis becomes parallel to the axis of the earth. In either position the plane of rotation of the eddy is tilted, and the outline of the eddy becomes elliptical.

The ideal shape of a precessing eddy is an ellipse whose shorter diameter, b, divided by its longer diameter, a, equals the cosine of the latitude, ϕ. The direction of elongation extends northwestward in the Northern Hemisphere and northeastward in the Southern Hemisphere at such a bearing from the north (α) that $\cot \alpha = \cos \phi$. The ideal proportions of a fixed eddy are $b : a = \sin \phi$; the direction of elongation is N. 45° W. in the Northern Hemisphere and N. 45° E. in the Southern.

A sand bar, Halfmoon Island, partly surrounding a tidal eddy in Chesapeake Bay has the proportions and orientation of the ideal precessing eddy. Other bars of similar shape are more or less filled with salt marshes like the fresh-water bogs called the Carolina bays. The Carolina bays have the proportions and orientation approximating those of the ideal fixed eddy. They occur at various altitudes within the tidal ranges of several marine terraces. The most symmetrical of the Carolina bays are interpreted as the sites of former tidal eddies.

HYPOTHESES OF ORIGIN

Webster's Dictionary records as one definition of the word *bay* "a tract of land (usually of prairie more or less surrounded by woods) containing a deep accumulation of humus, muck, or peat." The word is widely used in this sense throughout the Southeastern States, particularly in the Coastal Plain, where it is applied to all shapes and sizes of bogs. The term "Carolina bay," coined by Melton and Schriever (1933) and as used here, applies particularly to ovate, oval or elliptical bays, many of which are partly enclosed by low sandy ridges. Prouty (1952, p. 170) states that there are hundreds of thousands of such elliptical, sand-rimmed, and oriented depressions in the Coastal Plain between northern Florida and New Jersey.

Probably all geologists who have investigated the Carolina bays would agree that they have passed through a stage as lake or pond, though the basins are now more or less boggy. Some bays still enclose bodies of open water. The differences of opinion about them relate chiefly to the origin of the lake basins and of the rims. Melton and Schriever (1933) and Prouty (1952) attribute these features to a shower of meteorites, Johnson (1942) to upwelling artesian springs, and Grant (1945) to the hovering of fishes while spawning. In the present writer's opinion (Cooke, 1933, 1940, 1943, 1945a), nearly all the bays are original hollows in the surface of marine terraces; and the sandy rims are bars, beaches, spits, and dunes built by currents, waves, and winds. The purpose of the present paper is to explain why these secondary features are elliptical.

Proponents of the meteoritic hypothesis were impressed by the elliptical shape, the parallel orientation, and the conspicuousness of the rims when viewed from the air. These characteristics reminded them of a meteorite shower. Their subsequent investigations have consisted chiefly of the search for magnetic anomalies that might indicate buried meteorite fragments. When these searches proved inconclusive, Prouty (1935) proposed as a modification that air-shock waves from small missiles might blow out large, shallow holes. This hypothesis is dismissed by the present writer as implausible.

The great abundance of the bays, their occurrence far above the areas of artesian flow, and the impossibility of maintaining an artesian head in the surficial strata are convincing arguments against Johnson's artesian-spring hypothesis.

The rounding effects of waves and wave-induced currents during the lake stage appear to be an adequate explanation for the shape of the sandy shores of many asymmetrical or crooked bays. However, a considerable number of bays show such remarkable symmetry and such perfect parallelism (pl. 46) that random rounding seems precluded. The strange "coincidences" that the ratios of the diameters of the most perfect ellipses approximate the sine of the latitude and that the direction of elongation of these same bays trends almost exactly N. 45° W., bisecting two cardinal directions, indicate that some cosmic cause must be involved, presumably the rotation of the earth.

The elliptical shapes of the bays are possibly caused by the gyroscopic effect of the rotation of the earth on a rotating body of water, an eddy. As has been already stated (Cooke, 1940, 1943, 1945a, 1950), this effect is to alter the outline of an eddy from the initial circular shape to an ellipse of definite proportions and orientation. Because the proportions and trend of the more symmetrical Carolina bays approximate the theoretical features of an eddy, these bays are conceived of as having once contained eddies, which to some extent rounded the shores but whose principal work was the building of submerged bars.

This hypothesis of origin attributes the multiple ridges found in many bays to changes in the velocity of the eddy, which would increase or diminish its diameter and change the location of bar-building. The intersection of ridges might be brought about by a shifting of the center of rotation. Partial or isolated ridges may indicate a stopping of the eddy before the building of the bar had advanced far toward completion. Pear-shaped bays, whose direction of elongation generally deviate from that of the ideal eddy, may have been partly shaped by eddies of short duration. Occurrence of these features has been used as arguments against the theories of terrestrial origin and in favor of the meteoritic hypothesis.

A weakness of the eddy hypothesis as originally formulated (Cooke, 1940, 1943, 1945a) was the lack of a satisfactory mechanism for keeping the eddies in motion long enough to produce noticeable effects. Strong, continuous winds were postulated, but winds are notoriously fickle. A more reliable motive force is the power of the tides. Tides flow continually, day after day, year after year, as long as the passages connecting the tidal basin with the sea remain open.

If tides furnished the motive power by which the Carolina bays were shaped, the rims must have been built in inland estuaries or on tidal flats while the coastal terraces on which they lie were still submerged. The bays must be of different ages, the oldest on the higher terraces, which emerged first.

Sincere thanks are due to Dr. R. B. Blizard, of the Sperry Gyroscope Company, and to Prof. Gilbert N. Plass, of the Johns Hopkins University, whose frank criticism of an earlier draft of the manuscript lead to drastic revision. It is hoped that the present version is more intelligible though the conclusions remain unchanged.

IDEAL OUTLINES OF AN EDDY

As early as 1938 it was suspected (Cooke, 1940) that a rotating current, an eddy, tends to assume an elliptical shape of definite orientation. To prove this assumption mathematically and so to derive formulas for the shape and orientation of an eddy would require the manipulation of complicated hydrodynamical equations far beyond the mathematical ability of the writer. However, it may be assumed that a drop of liquid moving in a curved path obeys the same laws of motion as a solid particle moving in a curved path and that a rotating body of a liquid will behave in the same manner as a rotating solid body except insofar as its action will be modified by its lack of rigidity.

An eddy differs from a spinning flywheel in that the effect of gravity is not concentrated at the center of mass but attracts each particle independently. So any tendency of the rotating liquid to rise above the level of static equilibrium would be balanced against the weight of the particles so displaced. If the plane of rotation were tilted, the centrifugal force would be directed at an angle to the surface of static equilibrium. The vertical components of the centrifugal force would be balanced against gravity, and the surface would not tilt to the same extent as the plane of rotation. The horizontal components of the centrifugal force would not be opposed by gravity but would operate in the normal manner. However, as the plane of rotation is tilted, the intensity of the horizontal components would vary from unity along the axis of tilt to the cosine of the angle of tilt at right angles to that axis, and the horizontal outline of the eddy would become an ellipse, the horizontal projection of the tilted circle of rotation.

A spinning flywheel has gyrostatic properties which, though deduced empirically, are based on the fundamental laws of motion, which apply to all kinds of matter, liquids as well as solids. So, by attributing gyrostatic properties to liquids, it may be possible to arrive at tentative conclusions as to the shape and orientation of an eddy even though such conclusions lack mathematical proof.

Because of its inherent inertia every particle of matter resists change in the direction of its motion. This resistance is manifested in the gyroscope, an adaptation of the flywheel. A spinning flywheel tends to keep the direction of its plane of rotation fixed in space. If one tries to tilt the wheel, it offers resistance and tilts (precesses) at right angles to the direction of the pressure (fig 22). If it is forced to yield, it sets itself perpendicular to the axis about which it is forced to tilt (fig. 23). An eddy presumably responds in the same manner, though gravity holds its surface nearly horizontal.

The rotation of the earth on its axis is continuously turning the surface of an eddy out of its plane of rotation. The eddy, like a spinning flywheel, may react in either of two ways: the plane of the impulse to rotate may precess about the east-west diameter of the eddy or the plane may set itself perpendicular to the axis of the earth, about which it is forced to revolve. In a precessing eddy the plane will slope downward toward the equator at an angle equal to the latitude, ϕ, in which position the force causing it to precess is at its maximum; in a fixed eddy the plane slopes downward toward the nearer pole at the angle of the colatitude, $90°—\phi$.

The projection of a circle tilted at the angle ϕ is an ellipse whose proportions are such that the ratio of the

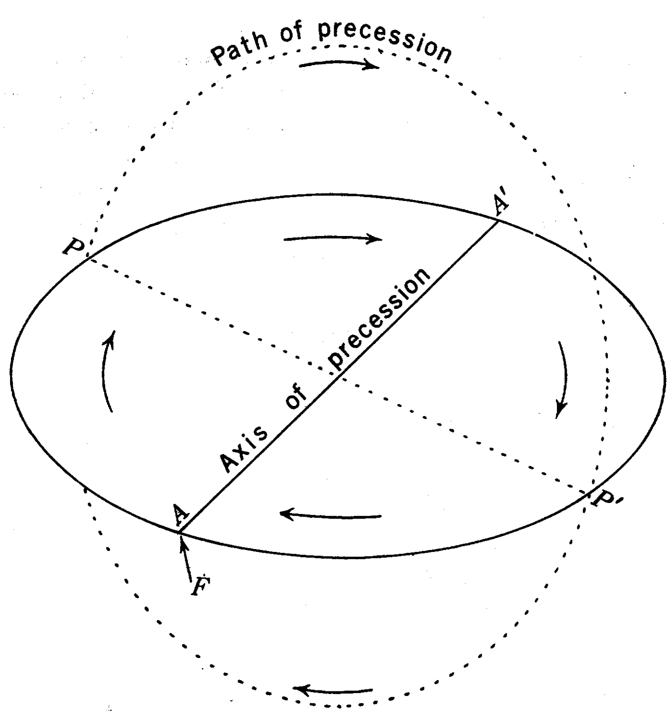

FIGURE 22.—Axis and path of precession of a rotating disk. If pressure (*F*) be applied at *A*, tending to tilt the disk about the axis *P–P'*, the disk will tilt (precess) about *A–A'*, and the fixed points *P* and *P'* will follow the dotted path of precession.

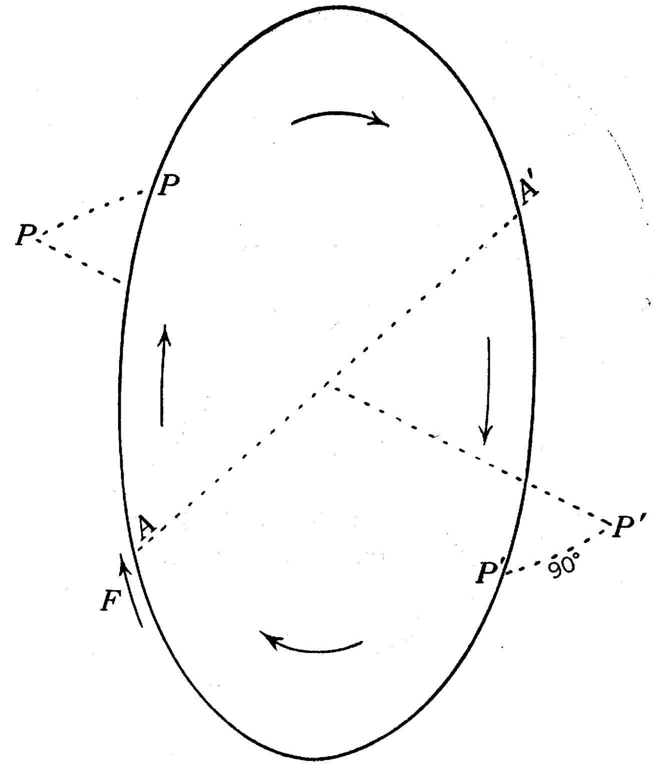

FIGURE 23.—Passive position of a rotating disk. If the rotating disk shown in figure 22 is compelled to turn about the axis *P–P'*, it will twist through 90° into the position shown, in which position it offers no resistance to being turned about *P–P'*.

shorter diameter (b) to the longer diameter (a) equals cosine ϕ. The projection of a circle tilted at the angle $90°-\phi$ is an ellipse whose proportions are $b:a=\sin\phi$ (fig. 24).

Because the plane of the impulse to rotate is tilted about the east-west diameter of the eddy, no matter whether the plane is fixed or precessing, one might suppose that an eddy would foreshorten along its north-south diameter so that the longer diameter would extend due east and west, as would be true of the projection of a stationary body. This supposition is false.

Let us first consider the fixed eddy, in which the plane of the impulse stands perpendicular to the axis of the earth. In this tilted position the rotation of the earth causes the eddy to describe a circle in space. Like the apparent motion of the sun and stars, this motion can be resolved into a vertical clockwise rotation from east to west as viewed from the north and a horizontal clockwise rotation as viewed from above in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. These two rotations are one-quarter phase apart. Consequently, the horizontal projections of points along the east-west diameter of the circle will shift back and forth along a line extending N. 45° W. in the Northern Hemisphere or N. 45° E. in the South-

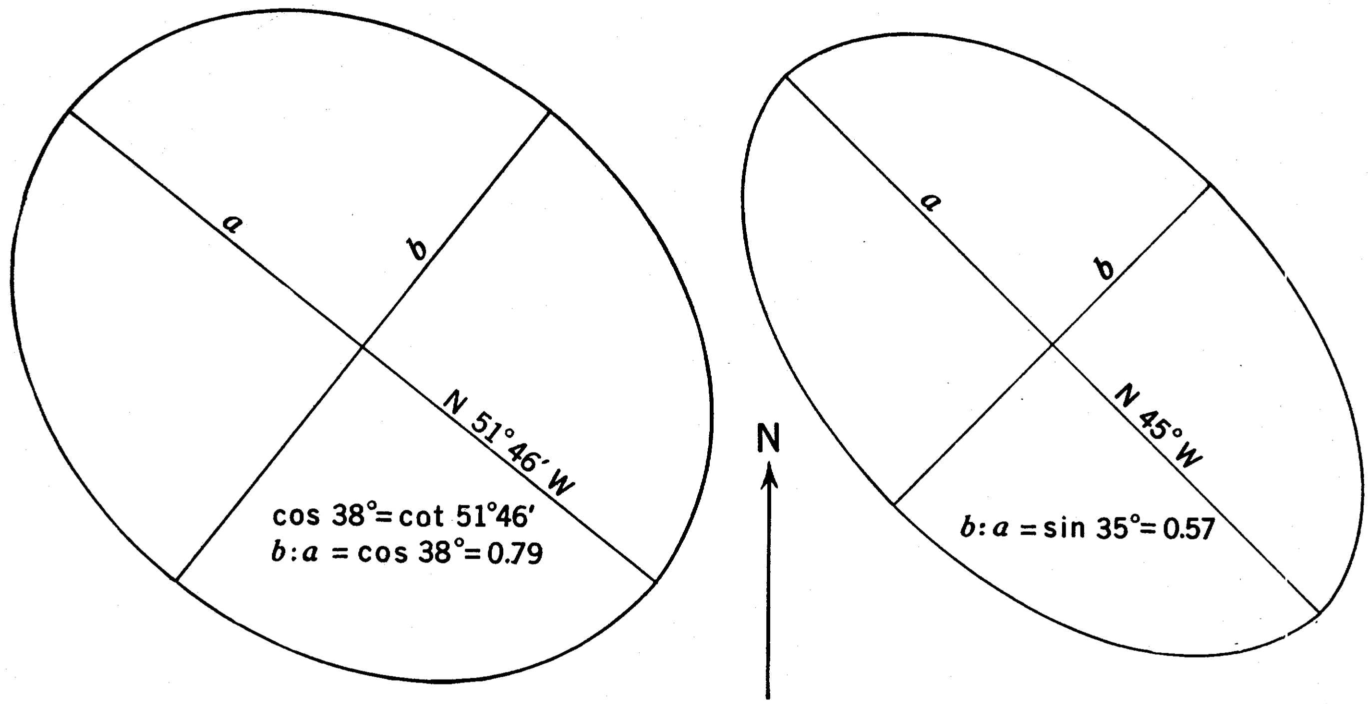

FIGURE 24.—Ideal shapes of a precessing eddy at latitude 38° N. (left) and of a fixed eddy at latitude 35° N. (right).

ern Hemisphere, and the longer diameter of the projection of the fixed eddy should extend in that direction.

The orientation of a precessing eddy differs from that of a fixed eddy because the plane of impulse turns with the earth. There is no apparent rotation, for the plane remains tilted about the east-west axis, parallel to the axis of the earth. However, the plane is actually turning about the axis of the earth while it precesses at the same speed about an east-west axis. The resultant axis lies midway between the axis of the earth and an east-west horizontal line. The direction of the horizontal projection of this axis should be the direction of elongation of a precessing eddy. This direction can be determined graphically as follows:

In a circle of unit radius (fig. 25) draw the north radius *NO* at a right angle to the diameter. Construct the angle *NOP* (ϕ), and project its cosine *OB* on the north radius. Then *B* represents the projection of the northernmost point on a tilted circle of radius *OP*. Connect *B* with *A* and bisect *AB* at *C*. *C* lies on the projection of the inclined axis, and *OC* shows its direction. As the triangle *OCB* is isosceles by construction, angle *BOC*=angle *CBO*. The angle *BOC* (α) equals the bearing from the north of the projected axis, the direction of elongation of a precessing eddy.

From the diagram (fig. 25) a general equation for the bearing (α) in terms of the latitude (ϕ) can be derived as follows:

$OB:OP=\cos\phi$

$OB:OA=\cot\alpha$

$OP=OA=1$

$\therefore \cot\alpha=\cos\phi$

So the ideal shape of a precessing eddy (fig. 24, left) should be an ellipse whose dimensions have the proportions $b:a=\cos\phi$ and whose longer axis deviates from the north by an angle α whose value is such that $\cot\alpha=\cos\phi$.

The general direction of elongation of a precessing eddy is the same as that of a fixed eddy, west of north in the Northern Hemisphere, east of north in the South-

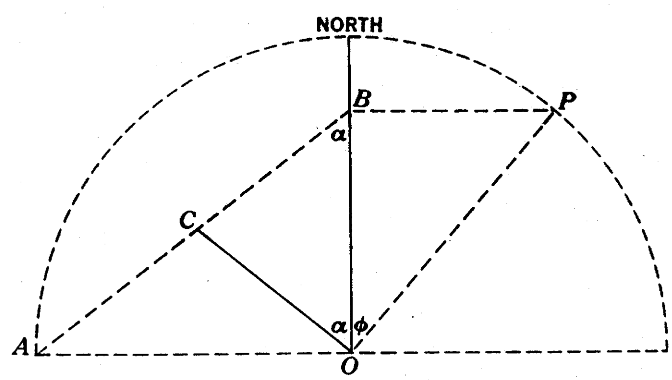

FIGURE 25.—Determination of the direction of elongation of a precessing eddy at latitude ϕ. *OB* is the horizontal projection of the north radius of the eddy, which is parallel to the axis of the earth; *OA* is the west radius, which lies on the axis of precession. *AB* is bisected by *C*, which therefore lies on the projection of the resultant axis, which is the direction of the elongation (α) of the eddy.

ern Hemisphere; for fixed points on the eddy that are moving eastward are simultaneously moving toward the equator regardless of the direction of the precession, and the projected diameters are rotated clockwise in the Northern Hemisphere and counterclockwise in the Southern.

STRUCTURES BUILT BY EDDIES

It has been shown that the ideal shape of an eddy should be either one of two ellipses having definite proportions and of different orientations. These shapes were deduced from the gyrostatic properties of matter, which are known for solids and inferred for liquids. The actual shape of an eddy is evanescent and intangible; but if the eddy continues to rotate for a long time at the same location it may, under favorable conditions, become surrounded by a bar of sand or mud dropped where the current slackens. Such a bar should approximate the shape of the eddy beside which it accumulates. If such bars conform in shape and orientation to the hypothetical shape and orientation of an eddy as here inferred, they offer convincing evidence that the actual outline of an eddy may approximate the ideal. Moreover, one can infer that an elliptical bar whose proportions have the sine ratio and whose *a* axis extends N. 45° W. was built around a fixed eddy, whereas a bar having the cosine ratio and whose orientation satisfies the equation $\cot \alpha = \cos \phi$ was built by a precessing eddy.

Illustrations of both types of bar are presented in this paper. Sand bars that conform very closely to the ideal shape and orientation of a precessing eddy are of fairly common occurrence on the Eastern Shore of Maryland and Virginia (pls. 41–45). One of them (pl. 41) still encloses a tidal eddy, but others are partly or completely filled with salt marsh or bog. Sand bars conforming to the shape and orientation of a fixed eddy surround some of the Carolina bays, which are out of the present reach of tides (pls. 46–53). Some other Carolina bays, of less symmetrical shape, may once have enclosed eddies that changed from fixed to precessing or vice versa.

STATIONARY TIDAL EDDIES

An eddy is formed between two currents flowing in different directions, between a current and quiet water, and where a current flows past an obstruction. Eddies may migrate with the current, or they may be stationary above or below an obstruction. Tidal currents are particularly productive of stationary eddies because they commonly flow through or into wide bodies of otherwise quiet water.

In many estuaries tidal currents flow continually, with only brief pauses approximately every 6 hours, when the direction of the current reverses. If the main current is restricted to a rather definite channel, such a reversing current can give rise to a permanent lateral eddy whose flow is always in the same direction. The incoming tide has a definite direction, which determines whether the resulting eddy will flow clockwise or counterclockwise. Once set in motion, the eddy might have sufficient momentum to continue its rotation during the brief interval at high tide while the direction of flow in the main channel is reversing. At ebb tide the eddy has no directional impulse other than its momentum, and the eddy may continue to rotate in the same direction as during flood tide, just as water circulates in an emptying washbasin in whichever direction the circulation is started.

EDDY-BUILT BARS OR NEPTUNE'S RACETRACKS

If eddies have a definite shape and orientation, a stationary eddy, under suitable conditions, should be able to impress that shape and that orientation upon the container. Let us consider a stationary eddy in a tidal lagoon floored with loose sand or silt and rotating either continuously in one direction or reversing its direction with each change of tide. Entering rapidly through the inlet, the incoming tide scours sand from its narrow channel and scatters it along its course, gradually building a bar into the lagoon, following the curvature of the current. Eventually the bar may almost encircle the eddy, leaving a gap at the inlet. Wind-driven waves may heap up the sand above tide level, converting the bar into a beach ridge, which may be capped by dunes.

In the course of time water plants may take root in the shallower parts of the lagoon, and their continued growth will slow up and eventually stop the eddy. Further silting and growth of plants may change the lagoon into a tidal marsh partly encircled by an elliptical sand ring. Finally, if sea level falls the tidal marsh will be replaced by a fresh-water bog resembling in every respect the so-called Carolina bays.

If the sea withdraws from a permanent eddy, there will remain a basin partly encircled by an elliptical ridge broken by one or more gaps where inlets had been. The proportions of the ellipse should be such that the ratio of the length of the shorter diameter to the length of the longer diameter would approximate either the sine or the cosine of the latitude. Moreover, the ellipse should bear a definite orientation.

These specifications are met by Neptune's racetracks, the name applied to the definitely oriented, elliptical sand rings (pl. 47) that surround some of the Carolina bays. This name was first used orally by the writer (Cooke, 1933) in an address to the Geological Society of Washington on March 22, 1933. It first appeared in print 12 years later as the title of a fanciful article in the Scientific Monthly (Cooke, 1945a). Neptune's racetracks seems appropriate not only because the shape of the rings resembles a racetrack but because the tides and the waves ("Neptune's horses") played an essential role in their construction. The marine origin of the racetracks in the manner postulated was indicated by the recent discovery of similar features in the shallow tidal waters of Chesapeake Bay. (See pls. 41–45.)

OCCURRENCE OF EDDY-BUILT BARS

RELATION TO THE CONTEMPORARY SEA LEVEL

Emerged elliptical bays and the surrounding Neptune's racetracks are not confined to any one level. They are most abundant at certain levels that correspond very closely with the altitudes of the shorelines of several marine terraces as determined from other criteria. Because the tide level has ranged through the entire gamut from the present sea level to that of the highest marine terrace, it would not be surprising to find shore features at intermediate levels, but all the racetracks that have been considered in this study fall very close to altitudes of well-established marine shorelines.

In previous papers (Cooke, 1925, 1930, 1931, 1936, 1945a, 1945b, 1952), the writer has called attention to emerged shorelines about 270 feet, 215 feet, 170 feet, 145 feet, 100 feet, 70 feet, 42 feet, 25 feet, and 6 feet above the present sea level. The occurrence of elliptical bays and Neptune's racetracks on several terraces at altitudes very near that of their supposed contemporary sea level is mutually corroborative evidence of the actuality of the shorelines and of the hypothesis that the racetracks were shaped by tidal currents. The presence of racetracks on the marine terrace yields one more criterion for the determination of the altitude of the contemporary sea level.

If Neptune's racetracks were formed by tidal eddies, one would expect to find the bars somewhat lower than the contemporary high-tide level through most of their circuit, and they should be broken by gaps where the tidal inlets had stood and where the bars were left uncompleted. Locally they might stand above tide level where the eddy had touched the shore. The bays (bogs) within the ridges would have originally been lower than sea level, but they might have been silted up to sea level as tidal marshes or they might have been filled higher by fresh-water alluviation or by windblown sand. In any event, the top of the ridges, when properly evaluated, should give an approximation to the height of the contemporary high-tide level.

SILVER BLUFF (6-FOOT) SEA LEVEL

The name Silver Bluff (Cooke, 1945b, p. 248) has been applied to a shoreline approximately 6 feet above the present sea level. The name is derived from a bluff at Miami, Fla. (Parker and Cooke, 1944, p. 24), where a wave-cut cliff of Miami oolite is separated from the shore of Biscayne Bay by an alluvial plain. Similar evidences of a strand line about the same level have been recognized in the Hawaiian Islands by Stearns (1938, p. 627), who named it the Kapapa strand. Elliptical bars, probably referable to the 6-foot stage, occur on the Eastern Shore of Maryland and Virginia in the vicinity of Pocomoke Sound, an arm of Chesapeake Bay.

Accomac County, Va.—Plate 41 shows a photograph of an area adjacent to Pocomoke Sound in the Parksley quadrangle, Accomac County, Va., at and near latitude 37°49′ N., longitude 75°44′ W. The nearest settlement is Hopkins, a fishing village just off the southwest corner of the photograph; and Parksley lies three miles farther east. Crisfield, Md., lies 13 miles northwest.

The curved spit, Halfmoon Island, is separated from the marshes of Webb Island by a narrow sandy channel, which is dry at low tide. Halfmoon Island consists primarily of a firm, sandy, curving beach fringed on the west by tidal marshes of uneven width which reach a maximum of 500 feet at the northern end. The entire spit lies less than 5 feet above high-tide level. The present maximum tidal range appears to be about 2 feet. The curve of the beach is continued under water beyond Halfmoon Point by a slightly submerged bar.

Halfmoon and Webb Islands shut off from Pocomoke Sound a body of water named The Thorofare, which is the widened extension of Hunting Creek, below Hopkins. The middle part of The Thorofare is occupied by a broad drowned channel at least 10 feet deep as indicated by soundings recorded on the chart of the coast. On each side of this channel the water is so shallow that one can wade far out from shore. East of The Thorofare lie broad salt marshes that extend about 2 miles to the mainland. The outer curve of the marshes is almost a counterpart of Halfmoon Island, although it is broken by an indentation at the mouth of a tidal inlet. Along this curve patches of sandy beach alternate with peaty deposits.

Halfmoon Island and the opposite marshes were visited by Harold I. Saunders and the writer by canoe from Hopkins on May 23, 1950. An attempt was made to determine the direction of the currents in The Thorofare, but a strong wind blowing from the southeast made observation difficult and the results inconclusive. Observations were continued on Halfmoon Island from about two hours before until about half an hour after low tide and thereafter for an hour or more on the opposite shore. Throughout this time there appeared to be a gentle clockwise drift on both sides of The Thorofare. This current was not strong enough then to roll sand grains along the bottom, though it might determine the direction of drift of sand or silt dislodged by breaking waves. It is supposed that Halfmoon Island was built as a slightly submerged bar when sea level stood about 6 feet higher and the tidal eddy was faster than now. The direction of the bar indicates that it was built by a clockwise current.

If Halfmoon Island and the opposing marshes were shaped by a precessing eddy, they should form an ellipse of such proportions that the ratio of its shorter diameter to its longer diameter should equal 0.79, the cosine of latitude 37°49′ N. The direction of its longer diameter should be N. 51°41′ W. as determined from the equation $\cot \alpha = \cos 37°49'$. An ellipse having these proportions and trend has been drawn on the photograph, plate 41. The reader can judge how well it fits the contour of the shores.

Somewhat similar features partly encircle Island Bay (pl. 42), a branch of Pocomoke Sound 3 to 4 miles west of Hopkins, at latitude 37°47′30″ N., longitude 75°46′ W., on the Chesconessex quadrangle. This area was not visited, but the photograph indicates a low, narrow, broken elliptical ridge in the tidal marshes bordering the bay. It seems evident that this ridge antedates the marshes that now separate it from the open water of Island Bay. The contour of the ridge fits the theoretical shape of a precessing eddy at that latitude. The development of marshes within the ellipse carries the process one step farther toward a feature comparable to the Carolina bays. The ridge seems to be a bar built by a counterclockwise eddy.

It seems probable that the ridges around Island Bay, like Halfmoon Island, date from late in the Pleistocene (late Sangamon), when sea level stood about 6 feet higher than the present. At that depth the ridges would have been submerged bars, and the present salt marshes would have been occupied by shallow open water. The greater depth would have permitted the current to circulate more freely within the bars, and the tidal currents passing up and down Pocomoke Sound would have had greater opportunity to keep the eddy in motion.

During the Silver Bluff stage, the tidal range on the Eastern Shore of Chesapeake Bay and in its tributaries may more nearly have approached that in the open ocean, which is now about twice as great as in the bay. This greater range of tide may have speeded up the currents in Pocomoke Sound and increased the velocity of the lateral eddies.

Somerset County, Md.—At the fishing village of Rumbley, latitude 38°5′ N., longitude 75°52′ W., in the Marion quadrangle in Somerset County, Md., 12 miles southwest of Princess Anne and 7 miles north of Crisfield, houses are strung out in single file along a V-shaped ridge averaging 100 feet or less in width and rising generally less than 5 feet above sea level (pl. 43). This V-shaped ridge appears to include adjacent segments of bars built by two tangent elliptical eddies, the northeasterly one flowing clockwise and the other counterclockwise. The soil consists of rather coarse, well-rounded sand grains mixed with much finer silt. Salt marshes occupy much of the area within the ellipses, except the drowned channels of Goose Creek and Teague Creek; and there are irregular areas of salt marsh outside the ellipses fronting Manokin River, an arm of Tangier Sound.

The actual direction of elongation of the two ellipses approximates N. 51°47′ W. very closely, the hypothetical bearing of the longer diameter of the trace of a precessing eddy at latitude 38°5′ N.; and the ratio of the diameters of the ellipses is very nearly 0.787, the ratio of the hypothetical eddy.

A smaller ellipse, representing a slightly more advanced stage of approach to the Carolina-bay type, is shown in plate 44. This ellipse lies 3 miles east of Crisfield, Md., at latitude 37°59′ N., in the Crisfield quadrangle. It is almost completely filled with salt marshes, which are drained by Gunby Creek into Pocomoke Sound. The orientation and proportions of this ellipse are nearly those of the ideal precessing eddy at this latitude. The eddy appears to have flowed counterclockwise.

Plate 45 shows elliptical clearings on a low sandy ridge in the Kingston quadrangle partly surrounding a swampy forest at the head of Annemessex Creek. This is crossed by the road to Rumbley 2 miles west of Westover in Somerset County, Md., at latitude 38°7′ N. The eastern point of the ridge is barely perceptible where it is entered by the road from Westover; but it is much more conspicuous where the road leaves it at the west. Here the ridge rises about 5 feet above the swamp. The dotted line on the photograph shows how well the natural feature fits the theoretical shape of a precessing eddy at that latitude.

All the known elliptical ridges in Maryland and Virginia lie at or below 5 feet above sea level. All approximate the orientation and proportions characteristic of a precessing eddy at the respective latitude. All are so situated that tidal currents passing up and down adjacent estuaries could have set the eddies in motion and kept them going. The conclusion seems justified that they were built by tidal eddies during the Silver Bluff stage, when sea level stood about 6 feet higher than now.

TALBOT (42-FOOT) SEA LEVEL

A shoreline at or a few feet higher than 42 feet above the present sea level has long been attributed to the Talbot terrace. This terrace is named from a county in Maryland, but it is well developed also in the Carolinas. The typical Carolina bays and Neptune's racetracks lie on the Talbot terrace.

Marion County, S. C.—A group of Neptune's racetracks named the Pee Dee Islands (pl. 46), in Marion County, S. C., northeast of Ariel Cross Road, lies within the Centenary quadrangle at latitude 34°5′ N. The group includes four well-shaped rings, of which two are tangent to each other. The four rings stand a little higher than 40 feet above sea level and reach 50 feet in two areas. The altitudes of two of the enclosed bays are 39 feet and 41 feet. So all of these features lie near 42 feet, the approximate altitude of the Talbot strand. The area forms a part of a Talbot estuary, which is now partly occupied by Back Swamp and Little Pee Dee River.

One of the elliptical Pee Dee Islands measures 0.52 mile by 1.02 miles; its ratio is 0.51. Another measures 0.58 by 1.08 miles, ratio 0.54. These ratios approximate 0.56, the sine of the latitude. The actual orientation of the Pee Dee Islands is very nearly N. 45° W., the orientation that theoretically should accompany the sine ratio. The assumption seems justified that the islands are bars deposited by fixed eddies. The two tangent bars seem to have been built by complementary eddies, the northeastern flowing clockwise, and the other counterclockwise.

Horry County, S. C.—Many of the elliptical bays in Horry County, S. C., appear to have been formed in tidal flats or lagoons connected with the Talbot sea. Cottonpatch Bay (pl. 47), 7 miles north-northwest of Myrtle Beach, lies slightly below 42 feet, and a point on the rim stands exactly 42 feet above sea level according to a spot elevation on the field sheet of the Nixonville quadrangle. Nine miles north-northeast of Myrtle Beach, three bays (pl. 48) reach 50, 51, and 52 feet above sea level. This group was formed behind a small barrier island that now stands nearly 60 feet above sea level. Possibly the level of these bays may have been raised by wind-blown sand, or high tide may have been higher there than elsewhere. The orientation of these bays approximates N. 45° W.

Brunswick County, N. C.—Many bays with faint, incomplete elliptical rims (pl. 49) are indicated on both sides of the 40-foot contour line on the map of the Southport, N. C., quadrangle. Spot elevations on nearby roads, which doubtless are higher than the bays, range from 44 to 52 feet above sea level. These bays, too, lie near the level of the strand of the Talbot terrace. During Talbot time, this region seems to have been a broad tidal flat fronting on the open ocean and crossed by low bars and swales, which directed the tidal currents laterally, causing eddies. The area shown in plate 49 lies about 4 miles northwest of Southport, about latitude 33°58′ N. The orientation is nearly N. 45° W.

PENHOLOWAY (70-FOOT) SEA LEVEL

The sea level corresponding to the Penholoway terrace stood about 70 feet higher than the present. Though the typical area is in Georgia, the terrace is well-developed in South Carolina, where the town of Summerville is built on a barrier island that rose above the Penholoway sea. A broad Penholoway lagoon, now partly occupied by Little Pee Dee River and its swamp, was bordered on the east by wide tidal flats in which eddies developed.

Horry County, S. C.—The map of the Nichols quadrangle shows Flat Bay at latitude 34°8′ N., 7 miles south of Nichols, in Horry County. The bay lies mostly below 70 feet, but points on its rim reach 71, 72, and 73 feet above sea level. It measures about 0.74 mile wide by about 1.33 miles long. These dimensions yield a ratio of 0.556, as compared with 0.561, the sine of the latitude. The direction of elongation coincides closely with N. 45° W., the hypothetical orientation of the trace of a fixed eddy.

Doe Bay and Gray Bay are two smaller tangent bays in the Duford quadrangle 3 miles southwest of Duford, Horry County, S. C. Both are nearly 70 feet above sea level, and points on the rim are 73 and 76 feet. The shape and orientation of both agree well with the hypothetical fixed eddy.

WICOMICO (100-FOOT) SEA LEVEL

Topographic maps of several quadrangles in South Carolina show the presence of elliptical bays on the Wicomico terrace. All the bays lie near the 100-foot contour line, which is the altitude of the Wicomico strand. They were separated from the open ocean by a chain of very low barrier islands.

Florence County, S. C.—Mill Bay (pl. 50) in Florence County, at latitude 33°58′ N. in the Lake City quadrangle 7 miles north of Lake City, lies less than 100 feet above sea level. The rim at the southeast end and on part of the northeast side barely rises above that altitude. This bay is less symmetrical than most of those described, but its overall proportions, ratio about 0.53, compare fairly well with those of a fixed eddy (ratio 0.559 at that latitude); and its general trend is about N. 45° W. It is as symmetrical as can be expected of a lake more than 2 miles long.

Marion County, S. C.—Grassy Bay, at latitude 34°13′ N. in the Marion and Mullins quadrangles 3 miles north-northeast of Marion, S. C., lies nearly 100 feet above sea level. An elliptical rim somewhat higher than 100 feet encircles it everywhere except along the southeast side, where the bay expands beyond the ellipse. The elliptical part of the bay measures 0.7 mile in width by 1.25 miles in length. The ratio of these is 0.56, and the sine of the latitude is 0.562. The trend of the longer diameter as shown on the map approximates the theoretical orientation of a fixed eddy, N. 45° W.

Maidendown Bay, at nearly the same latitude, 5 miles west of Mullins, is not quite symmetrical, being somewhat broader at the northwest end. The bay lies very nearly 100 feet above sea level. The highest part of the rim along the northern quadrant exceeds 110 feet. A benchmark at the northwest end is 105 feet above sea level. The rim is broken at the southeast end. The dimensions within the rim are approximately 1 by 1.86 miles, giving a ratio of 0.54. The trend of the elongation agrees with the theoretical orientation of a fixed eddy, N. 45° W.

Big Sister Bay (pl. 51) at latitude 34°11′ N. on the Mullins quadrangle, is tangent to Little Sister Bay on the east and Reedy Creek Bay at the southeast end. The rims around Big Sister and Little Sister are approximately 100 feet above sea level; that around Reedy Creek Bay is a trifle lower. Big Sister is the most symmetrical of the group and measures about 0.97 by 1.76 miles, giving a ratio of 0.55 as compared with 0.56, the sine of the latitude. The orientation is approximately N. 45° W.

The rims around Big Horsepen Bay (pl. 52) at latitude 34°9′ N. in the Mullins quadrangle barely exceed 90 feet above sea level. The water in which they accumulated presumably was deeper than that at other bays here described. The presence of multiple rims indicates that the center of the eddy shifted a little when they were being formed.

OKEFENOKEE (145-FOOT) SEA LEVEL

An ancient shoreline now standing between 140 and 150 feet above sea level was first detected in central Florida, where it is bordered by low sand dunes. Later, topographic indications of a shoreline near 140 feet were noticed in the District of Columbia (Cooke, 1952, p. 43, 48, 50). When the old Dean tract at Connecticut and Florida Avenues in Washington was graded in February 1953, these indications were verified by the uncovering of large, rounded cobbles abutting against a hill of schistose bedrock at an altitude of approximately 140 feet.

The Okefenokee terrace was named by Otto Veatch (Veatch and Stephenson, 1911, p. 35), who regarded it as marine but did not determine the altitude of its shoreline. The present writer (Cooke, 1925, p. 26–27) included in the Okefenokee terrace some areas near Okefenokee Swamp that are as high as 160 feet above sea level. He later recognized these as equivalent to the Sunderland terrace of Maryland and proposed (Cooke, 1930, p. 588) to suppress the name Okefenokee terrace in favor of Sunderland terrace, which latter name has priority (Cooke, 1931, p. 508). However, the typical part of the Okefenokee terrace is bounded by the recently discovered 145-foot shoreline, and the name Okefenokee terrace has been revived (MacNeil, 1950, p. 101).

Florence County, S. C.—Morris Bay in the Florence West quadrangle 4 miles east of Timmonsville, S. C., lies very near the Okefenokee shoreline. Its altitude is less than 140 feet above sea level, but its southeastern rim reaches at least 143 feet. The rim is lower than 140 feet or is wanting at the southern end and along the southwestern side. Morris Bay is very similar in shape, size, and orientation to Jacks Bay, which is shown in plate 53.

Sumter County, S. C.—Two small tangent bays in the Mayesville quadrangle 2.5 miles south of Mayesville, S. C., lie higher than 130 feet above sea level. The rim between them rises above 140 feet both north and south of the point of tangency.

Cumberland County, N. C.—A bay at latitude 35°4′ N., in the Vander quadrangle 4 miles east-northeast of Fayetteville, N. C., is less than 130 feet above sea level, but its rim stands higher than 140 feet on the northeast side. This bay measures 0.34 by 0.61 mile, which gives a ratio 0.56 as compared with 0.57 the sine of the latitude. The longer diameter trends very nearly N. 45° W., which is the theoretical bearing of a fixed eddy.

A bay at the eastern edge of the Vander quadrangle is crossed by the Atlantic Coast Line Railway at a point

6 miles east of Fayetteville. The bay is more than a mile wide, its altitude is less than 140 feet.

SUNDERLAND (170-FOOT) SEA LEVEL

The Sunderland terrace is bordered by a shoreline approximately 170 feet above sea level. Some of the elliptical bays in Darlington County, S. C., described by Glenn (1895), are on this terrace.

Darlington County, S. C.—Jacks Bay, (pl. 53) in Darlington County, is near the northwest corner of the Florence West quadrangle. It is crossed by the Atlantic Coast Line Railway 1 to 2 miles southwest of Syracuse. The bay lies approximately 165 feet above sea level, and its rim rises higher than 170 feet along the entire northeast side of the bay, touches 170 feet on part of the opposite side, but is lower or open on the southwest quadrant, where the tidal currents evidently had access to it.

The proportions of Jacks Bay are almost identical with those of the ideal fixed eddy at latitude 34°13′ N. Its dimensions, as scaled from the map, are 1 by 1.82 miles, which gives it a ratio of 0.556 as compared with 0.562, the sine of the latitude. Its orientation is very nearly N. 45° W.

Orangeburg County, S. C.—A conspicuous semicircular ridge borders the southeast and southwest sides of a bay in the Orangeburg quadrangle 1 mile east of St. George Church and 2 miles north of Rowesville, S. C. The present altitude of the bay is somewhat higher than 170 feet above sea level, but the bay may have been filled above the original tide level by the intermittent stream that now flows through it. The rim stands above 180 feet. Though incomplete, the ridge conforms to the shape of an ideal fixed eddy.

COHARIE (215-FOOT) SEA LEVEL

A group of 7 ½″ topographic maps (U. S. Geol. Survey 1953a, 1953b, 1953c) of the vicinity of Laurinburg, N. C., by 10-foot contour lines and green woodland overprint, show many elliptical bays similar in proportions and orientation to the Carolina bays already described but at higher levels. The bays fall into two groups near two different levels—one slightly lower than 215 feet, the other slightly lower than 270 feet above sea level.

Scotland County, N. C.—The bays of the first group lie on the Coharie terrace, whose shoreline stands about 215 feet above sea level (Cooke, 1930, p. 588). Worthy of mention are two bays in the Laurinburg quadrangle 1 to 2 miles southeast of Laurinburg. These are surrounded by the 210-foot contour line, and the swampy surface of one of them lies 208 feet above sea level. This bay measures 1.33 miles long by 0.8 mile wide, a ratio of 0.60, compared with 0.57, the sine of the latitude (34°47′ N.). Dunelike mounds encircling the southeastern edge of this bay reach 225 feet above sea level.

The southeastern half of the adjoining Wakulla quadrangle includes many bays of various sizes at approximately the same level. A bay south of the Laurinburg-Maxton airport is bordered on the east by a bar reaching slightly higher than 210 feet.

HAZLEHURST (270-FOOT) SEA LEVEL

The name Hazlehurst was proposed by Cooke (1925, p. 29) for a terrace typically exposed between Hazlehurst, in Jeff Davis County, and Baxley, in Appling County, Ga. The name was later rejected (Cooke, 1931, p. 506) in favor of Brandywine (Clark, 1915), which had 10 years' priority. The Brandywine terrace was regarded by Clark as the original surface of his Brandywine formation, which he thought was probably Pleistocene. But the Brandywine has since been interpreted as an alluvial fan, a fluvial deposit, probably of Pliocene age (Campbell, 1931; Cooke, 1952, p. 40). So the name Brandywine is not appropriate for a marine terrace of Pleistocene age.

The upper limit of altitude originally assigned (without adequate control) to the Hazlehurst terrace was 260 feet above sea level. Later it was raised to 270 feet (Cooke, 1931, p. 506).

Scotland County, N. C.—Bays in the Laurinburg quadrangle 4 miles north of Laurinburg stand about 250 feet above sea level, but the adjacent ridges (bars) exceed 260 feet. The maps of the Gibson and Wagram quadrangles show several small bays at the same altitude. A bay in the Ghio quadrangle is surrounded by the 260-foot contour line and bordered by ridges reaching 270 feet. This bay adjoins an upland reaching 320 feet, and evidently it lies at the shoreline of the Hazlehurst terrace.

SUMMARY

Liquids as well as solids have gyrostatic properties because all matter is subject to the fundamental laws of motion. Consequently, the plane of rotation of an eddy, when turned in space by the rotation of the earth, behaves like a gyroscope in that it either precesses about an axis at right angles to the axis of the earth or it sets itself perpendicular to the axis of the earth and remains fixed in that position.

In either instance the plane is tilted with respect to a horizontal surface: in the precessing eddy the plane of rotation lies parallel to the axis of the earth, tilted at the angle of the latitude, ϕ; in the fixed eddy the plane is tilted at the angle $90°-\phi$.

The centrifugal forces lie in the plane of rotation. The vertical components of the centrifugal forces are opposed by gravity. Consequently, the surface of the eddy is less steeply tilted than the plane of rotation. The horizontal components vary in intensity from a maximum along the axis of tilting to a minimum proportional to the cosine of the angle of tilting at right angles to that axis. So the horizontal outline of the eddy becomes an ellipse, the projection of a tilted circle.

The proportions of the ellipse projected from a precessing eddy are such that the ratio of the shorter diameter (b) to the longer diameter (a) equals the cosine of ϕ. The proportions of the ellipse corresponding to a fixed eddy are represented by the equation $b:a=\sin\phi$.

The precessing eddy has two simultaneous motions in space: it is revolving about the axis of the earth and it is precessing about its east-west diameter. The resultant motion is a turning about an inclined axis midway between the axis of the earth and an east-west horizontal line. The direction of this resultant axis, which is the direction of elongation of the projected ellipse, was determined graphically to satisfy the equation $\cot\alpha=\cos\phi$, where α represents the declination from the north.

The fixed eddy has an apparent motion like that of the sun, from east to west and from north to south (in the Northern Hemisphere), these rotations being one-quarter phase apart. This difference in phase shifts the axis of tilting 45° clockwise in the Northern Hemisphere, counterclockwise in the Southern Hemisphere, so that the elongation of the ellipse extends N. 45° W. or N. 45° E.

These conclusions are purely deductive and without experimental or mathematical verification. However, the validity of the deductions appears to be corroborated by the occurrence of elliptical sand bars, evidently built by circulating waters, that simulate very closely both the proportions and the orientation of the hypothetical eddies. One of these, though apparently built at a somewhat higher stage of sea level than the present, still encloses a tidal eddy. Others occupy marine terraces at higher levels.

In Chesapeake Bay there is a tidal eddy partly surrounded by a curved spit (Halfmoon Island, pl. 41) having the hypothetical shape and orientation of a precessing eddy. Other neighboring sand bars are partly silted up within; they show all transitions toward features resembling the Carolina bays. All these bars in and near Chesapeake Bay seem to date from Silver Bluff time, when the water level stood about 6 feet higher than now.

The most symmetrical of the Carolina bays have the shape and orientation of fixed eddies. The sand rings around them (Neptune's racetracks) are interpreted as bars, beaches, and dunes surrounding tidal eddies in former estuaries or on tidal flats. Most of the racetracks lie within the supposed tidal ranges corresponding to several marine Pleistocene terraces. The highest described forms part of the Hazlehurst terrace at an altitude of 270 feet.

PRACTICAL APPLICATIONS

The equations derived herein for the shapes and orientations of eddies may apply not only to closed currents (eddies) but also to open currents, as at river bends, in which the horizontal components of the centrifugal force should be identical with those in the corresponding segment of an eddy. Consequently, hydraulic engineers may be able to determine from the equations the stable shape of the shore line in rivers or beside headlands or jetties.

The equations may apply also to gases. If so, they may aid in the plotting of the direction of the wind around the vortices of hurricanes or in wind tunnels.

There appear to be no theoretical limitation as to the size or velocity of the circulating currents to which these equations apply. However, it seems probable that there is at least a lower limit to both of these factors beyond which the effects of the rotation of the earth would not be noticeable. All of the bays herein described are of considerable size, ranging from about half a mile to more than 2 miles in diameter.

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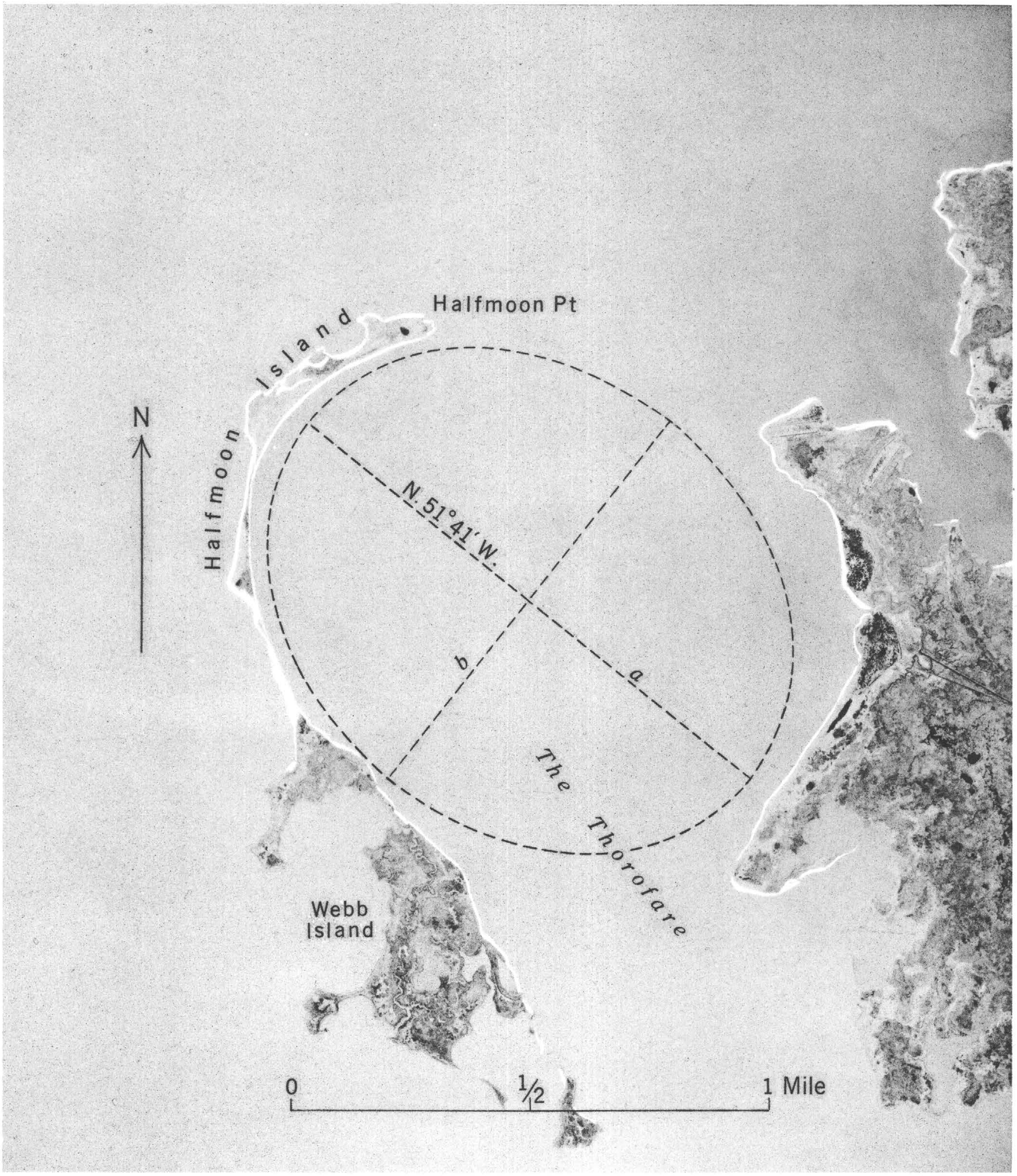
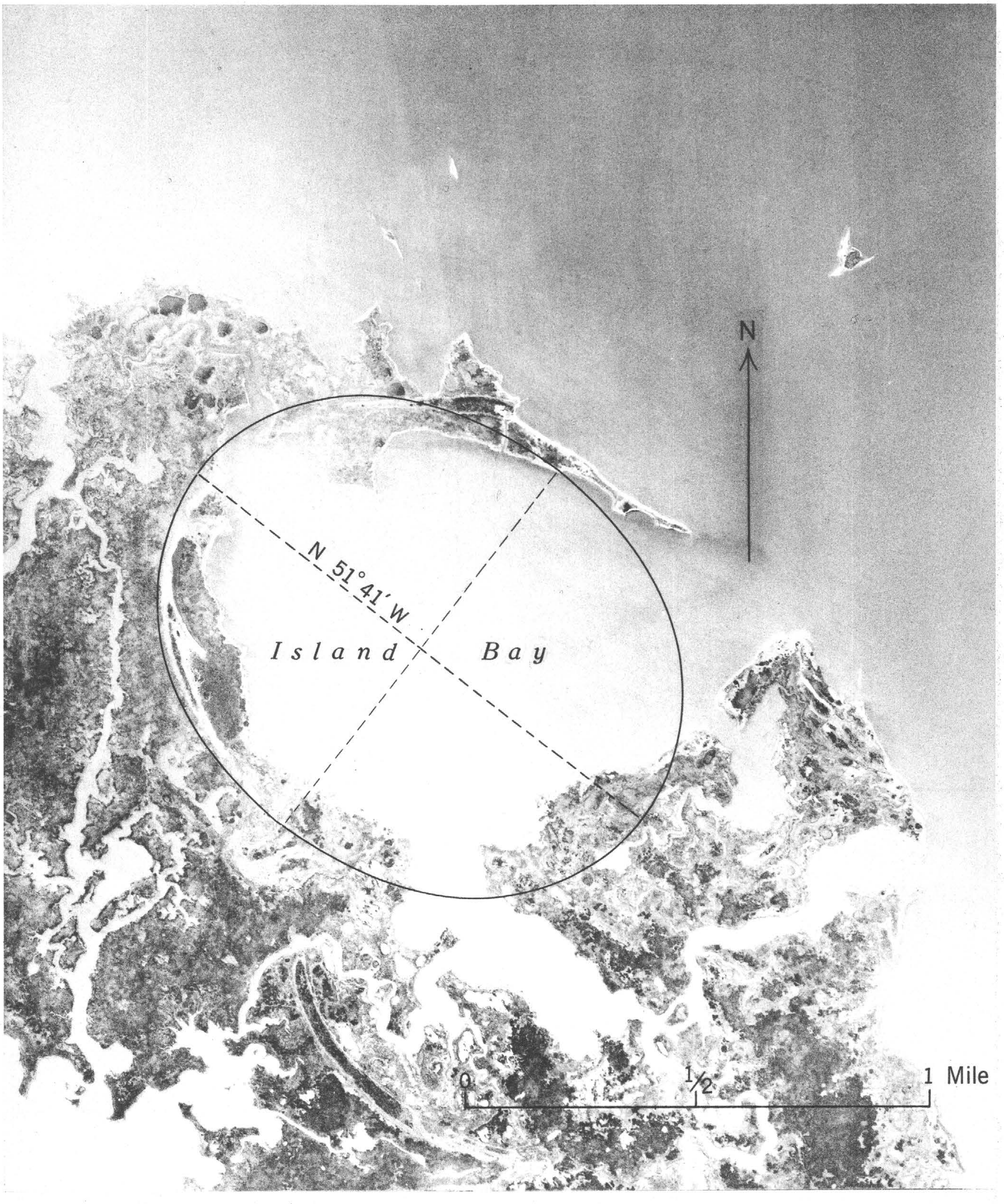
PLATES 41–53



HALFMOON ISLAND AND VICINITY, ACCOMAC COUNTY, VA.

A low spit partly surrounding a tidal eddy. The ellipse shows the hypothetical shape of an eddy at lat. 37°49′ N.

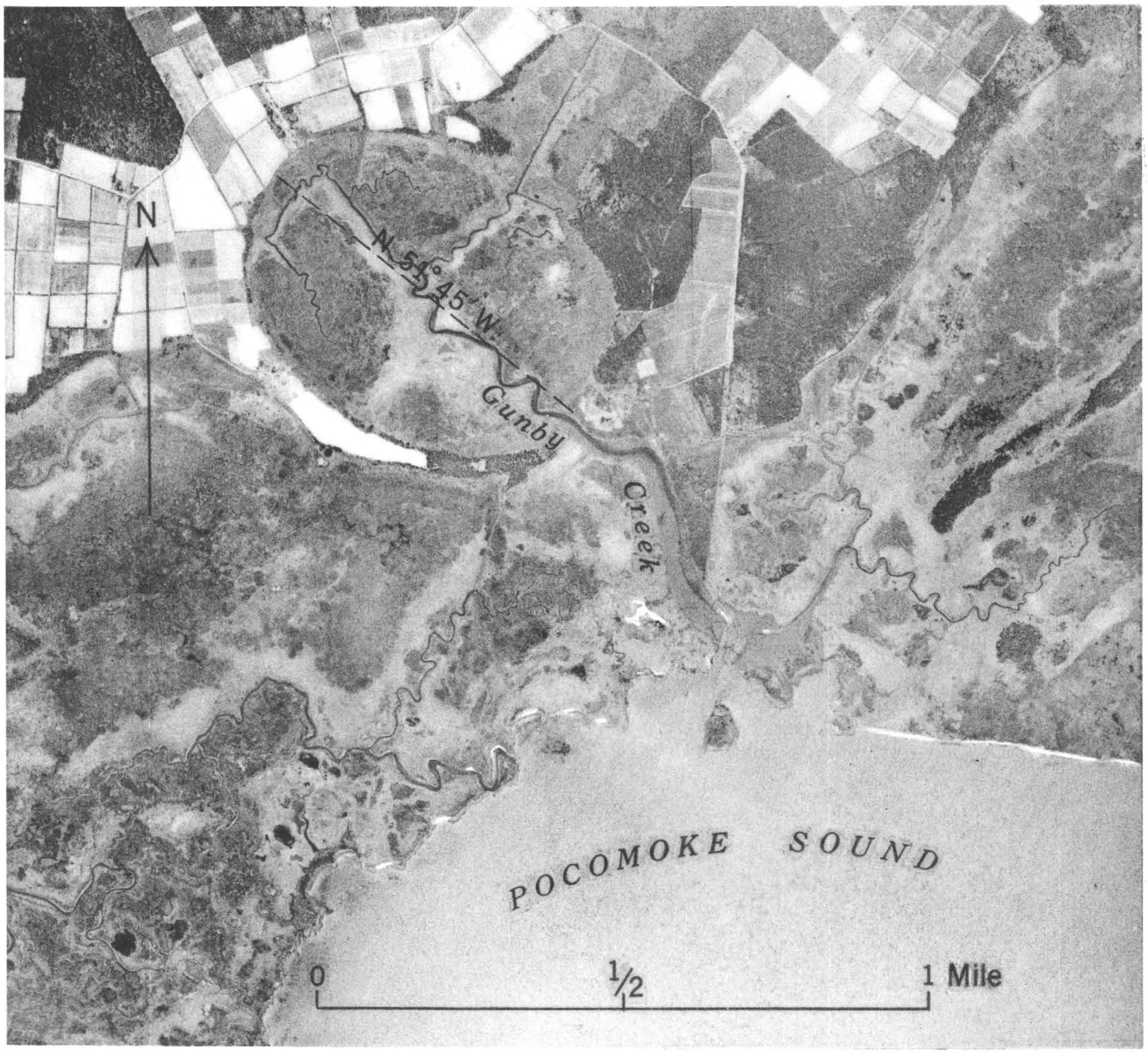


ISLAND BAY AND VICINITY, ACCOMAC COUNTY, VA.

Sand bars probably formed around a tidal eddy, now partly silted up. The ellipse shows the hypothetical shape of an eddy.

ELLIPTICAL RIDGES AT RUMBLEY, SOMERSET COUNTY, MD.

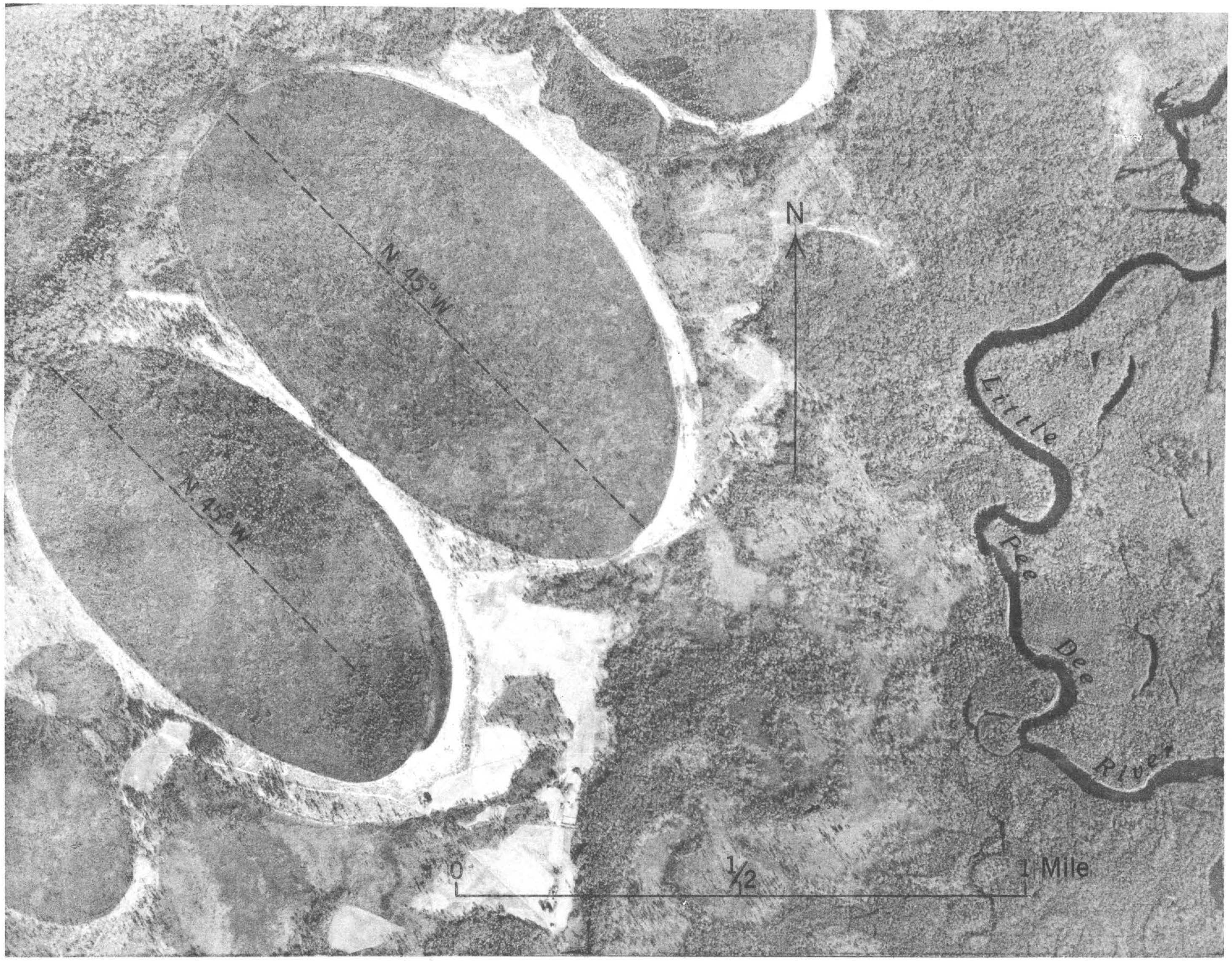
Bars built by two complementary eddies.



ELLIPTICAL MARSHES 3 MILES EAST OF CRISFIELD, MD.

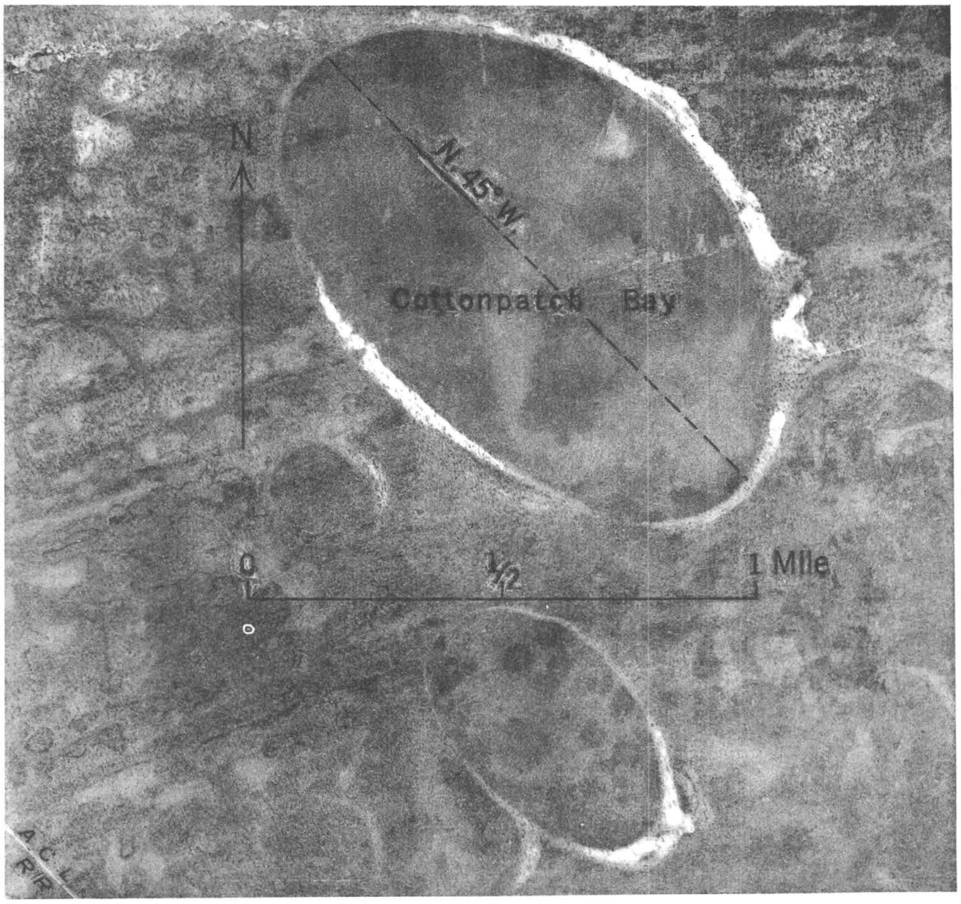
The direction of the dotted line was calculated from the equation cot a = cos ϕ.

ELLIPTICAL CLEARINGS 2 MILES WEST OF WESTOVER, MD.

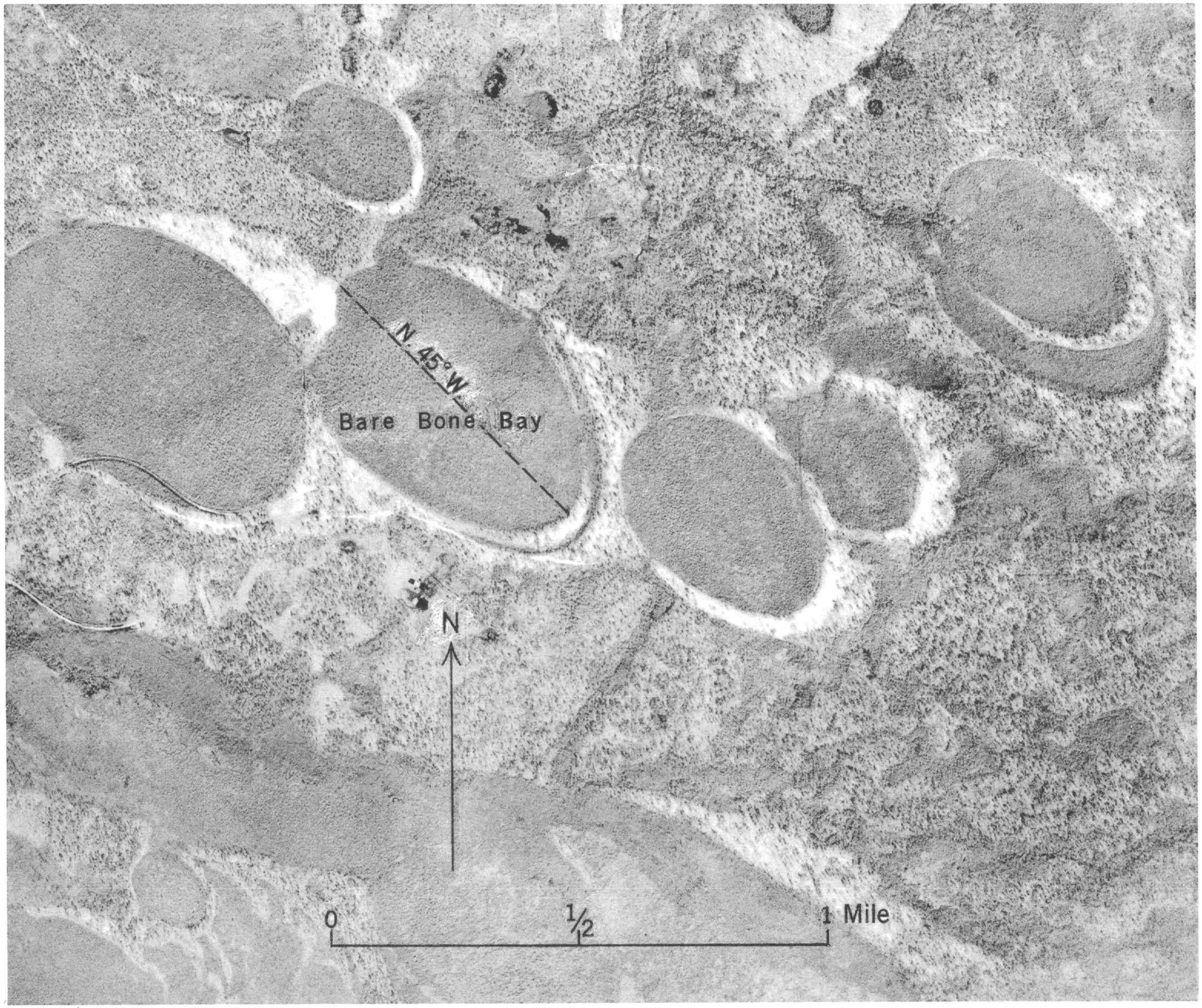


PEE DEE ISLANDS, MARION COUNTY, S. C.

Traces of two complementary fixed eddies.



COTTONPATCH BAY, HORRY COUNTY, S. C.
The trace of a fixed eddy.

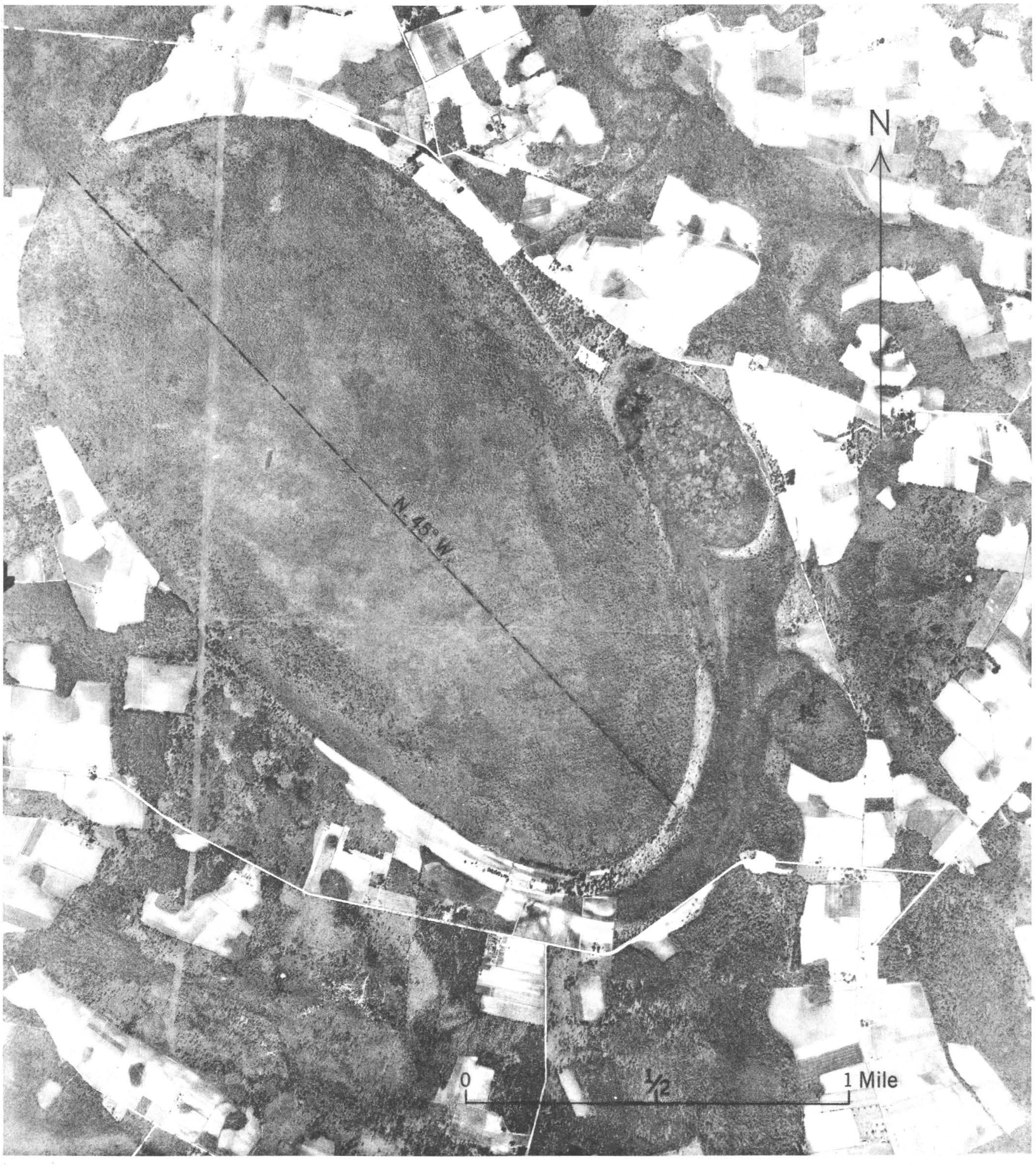


A GROUP OF BAYS IN HORRY COUNTY, S. C.

Traces of eddies in a tidal lagoon.

AN AREA IN BRUNSWICK COUNTY, N. C., 4 MILES NORTHWEST OF SOUTHPORT.

Markings probably made by tidal eddies on a tidal flat.



MILL BAY, FLORENCE COUNTY, S. C.

BIG SISTER BAY, MARION COUNTY, S. C.

BIG HORSEPEN BAY, MARION COUNTY, S. C.

JACKS BAY, DARLINGTON COUNTY, S. C.

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