[AMERICAN JOURNAL OF SCIENCE, VOL. 252, SEPTEMBER 1954, PP. 547-554]

ON THE ORIENTATION OF LAKE BASINS*

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ABSTRACT. A theoretical horizontal circulation system is described for a circular lake with a constant wind blowing across it.

The shape of many oriented lakes in northern Alaska indicates that their present circulation system approaches the theoretical one, and that it is this system to which they owe their orientation.

Because the Carolina Bays are oriented along the probable direction of the winds which excavated them they are believed to be deflation basins, and not lakes whose shape is due to wave action and water circulation.

INTRODUCTION

The oriented lakes of northern Alaska have been described in some detail by Black and Barksdale (1949). Briefly, these lakes occur in an area of some 25,000 square miles adjacent to the Arctic Ocean. They tend to be elliptical or sub-elliptical in shape, and they have the very curious property of an almost identical alignment of their long axes, which are oriented slightly to the west of north.

The coastal plain upon which the lakes lie is a region of perennially frozen ground, and it has been suggested that many of them owe their origin to local thawing and subsequent collapse of the ground. Others, from their spatial relations to each other and to raised strand lines, are believed to have originated by the dissection of raised lagoons.

The cause of the curious orientation shown by most of the lakes of the Arctic Coastal Plain has remained a problem until the present time. Black and Barksdale drew attention to the close similarity between many of the Alaskan lake basins and the Carolina Bays. They believed that the conditions under which the oriented basins of both Alaska and the Carolinas had been excavated were similar, and they felt that the directive influence was probably that of the prevailing wind. In their own words, "Prevailing winds in the direction of the long axis of the Alaskan lakes are believed to be the chief factor that controlled their orientation."

This hypothesis offered two difficulties. In the Carolinas the present wind is extremely variable in direction, and in Alaska the prevailing winds, especially the ones above 15 miles per hour in speed, blow almost across the oriented lakes, not along them.

Odum (1952) has recently removed the first of these difficulties. Making certain assumptions about Pleistocene weather systems, he has reconstructed a weather map for the Carolinas during a maximum advance of the continental ice sheet and has shown that the resulting winds would tend to blow along the long axis of the Carolina Bays.

It is the purpose of this paper to remove the second difficulty by showing that the present wind direction in northern Alaska is actually sufficient cause for the existing orientation of the Alaskan lakes.

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* A contribution from the Arctic Research Laboratory, Point Barrow, Alaska, and from the Osborn Zoological Laboratories, Yale University, submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Yale University. This work was supported by contract SAR-NONR-340(00) between Yale University and the Office of Naval Research of the United States Navy.

ACKNOWEDGMENTS

The field work upon which this study is based would not have been possible without the financial support of the Office of Naval Research and the assistance of Dr. Ira L. Wiggins of the Arctic Research Laboratory, Point Barrow, and his administrative staff. The ideas expressed are the outcome of many discussions with Mr. Kirk Bryan, Jr., and Mr. Richard Leahy, who were my companions in the field, with Professor E. S. Deevey, Jr., and Professor G. E. Hutchinson of the Zoology Department, Yale University, and with many other friends at Point Barrow and Yale University. I am particularly indebted to Dr. Robert Black of the U. S. Geological Survey, who first drew my attention to the problem of oriented lakes.

OBSERVATIONS AND DEDUCTIONS

This paper grew out of observations made during the summers of 1951 and 1952, while investigating the paleo-limnology of northern Alaska. During field work in the regions of Point Barrow, Umiat and East Oumalik, and airplane flights over other parts of the coastal plain, the accuracy of the observations which had been made by Black and Barksdale (1949) was abundantly confirmed. Examination of aerial photographs provided by the Office of Naval Intelligence and of the Alaska Reconnaissance series map sheets of the U. S. Geological Survey provided additional corroborative data.

Only one point of disagreement arose with the observations of the earlier workers. It concerned their belief that in lakes of width permitting a sufficient fetch the orientation was becoming more easterly in response to present wind conditions. Actually, although occasional lakes can be found which are assuming almost any possible shape and orientation, they tend to be small ones, generally residual lakes in the center of a partially drained basin. There was no detectable general trend toward a change in orientation, and day-to-day observations upon the response of the lake shore to wind, which were made necessary by the fundamentally limnological nature of the main investigation, led gradually to the belief that the lakes were still in very close balance with the forces which had originally caused their orientation.

Thaw lakes are very mobile. Their shorelines change rapidly under the influence of summer storms, changes of several meters during a single storm occasionally being observed. Quantitative data for rates of shoreline retreat and advance over extended periods are very rare, but some data are available for East Oumalik Lake (69°, 50″ N., 155°, 27″ W.).

This lake is retreating along part of its shoreline, leaving a gently sloping plain behind it as it goes. Among the plants colonizing this plain are shrub willows of several species. The age of the oldest willows growing at a spot on the plain gives a measure of the length of time since the lake receded from that spot. From the systematic data shown in figure 1 it can be seen that the rate of retreat has been well over a meter a year for the last 70 years.

It would be unsafe to apply this rate too widely, for rates of shoreline advance and retreat are extremely variable. No single thaw lake is typical of all the thousands upon the Arctic Coastal Plain, but observations on a large number of lakes during the summer storms of two seasons indicate that one meter a year is at least of the correct order of magnitude.

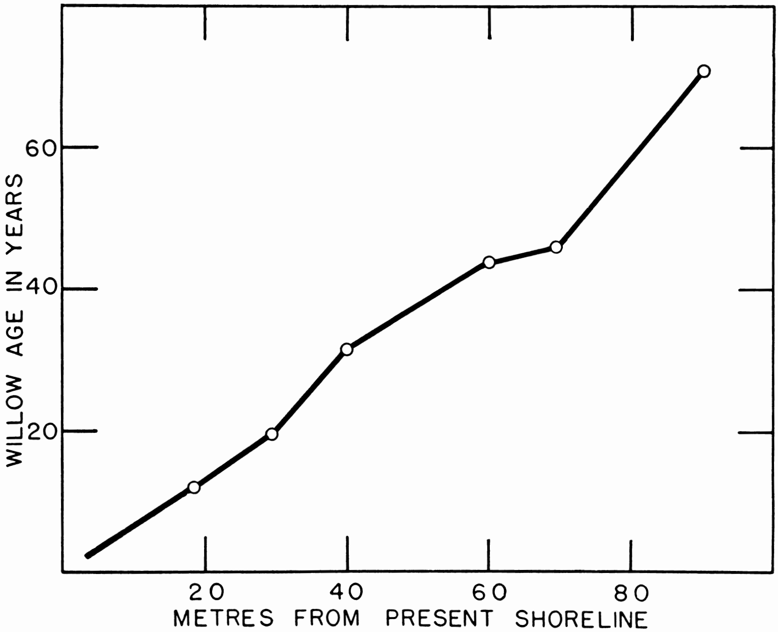

Fig. 1

At such a rate it would not take more than a few centuries for the oriented lakes to change their direction completely in response to a change in prevailing wind direction. The change to present wind direction which was postulated by Black and Barksdale (1949) must, then, have occurred during the last few centuries. It seems unlikely, from what is known of recent weather changes, that the direction of the northern Alaska winds could have changed by almost 90° in so short a space of time. In all likelihood the agency which imparted a common direction to the oriented lakes is still operative.

There are many possible sources of direction which are almost certainly negligible. The relief of the terrain is too slight for differential insolation to be important. The regional slope is too slight and too inconstant for the lakes to be stretched-out cryopedologic structures, even if structures of such a size were known. According to the best available evidence (Capps, 1931) the coastal plain is unglaciated, so the lakes cannot lie in or between glacially produced streamline forms. The mantle consists of a great depth of unconsolidated material (Payne, and others, 1951) which prevents bedrock topography from explaining the orientation of the lakes, and there is no geophysical evidence of a meteor shower (Black and Barksdale, 1949, p. 117). Of all the possible agencies only the prevailing wind seems at all likely.

It has always been assumed by people considering the problem that a lake being excavated or enlarged by the wind will grow fastest downwind. Blow-outs, at least in Alaska, actually do grow in this way, and it has been easy to reason by analogy that lakes should do the same. There is, besides, a certain intuitive probability to the idea that the shore which is under attack by the strongest waves is the one which will retreat fastest. There are, however, factors other than simple wave action which control the rate of shoreline retreat. Not only are currents necessary to carry away the material loosened by the waves but they are invariably produced whenever a wind blows over the water. In particular, a surface drift is produced which travels approximately in the direction of the wind, at least in shallow lakes.

It was formerly believed that the water brought to a shore by this surface current was returned by another which flowed along the bottom, the so-called undertow. Recent studies by Shepard (1948) on sea beaches have shown that this undertow is negligible, and that the return of water is by way of surface currents, called rip currents, which are nourished by longshore currents, and which flow out at right angles to the shore.

On sea shores it is sometimes difficult to understand the factors which govern the location of the return rip currents but for a small lake it can be shown that they are always at the ends.

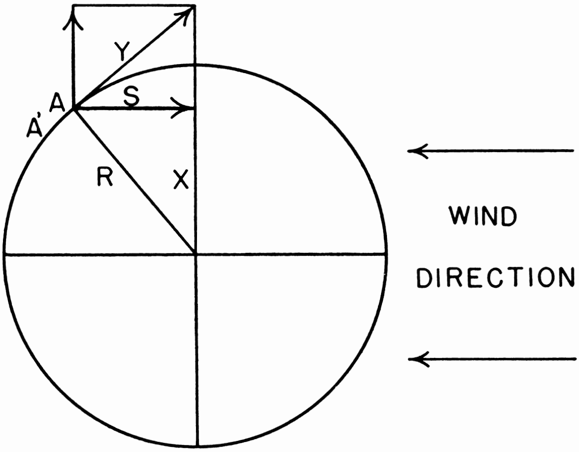

Fig. 2

Consider a small lake such as that shown in figure 2, shallow, filled with an ideal liquid, and over which a wind of uniform velocity is blowing. The wind will exert a force upon the surface of the lake which will cause a surface drift to flow across it. The rate at which water will be transported by this drift to any point *A* on the downwind side of the lake will depend upon the average velocity of the water arriving at *A*. This in turn will depend upon the width of the lake and also upon the acceleration. The actual relations are:

$$2s = u_a t$$

$$= \frac{at^2}{2} \quad (\text{because } u_a = \frac{at}{2}$$

$$t = \sqrt{\frac{4s}{a}}$$

Substituting this value of t in $u_a = \frac{at}{2}$

$$u_a = \frac{a\sqrt{\frac{4s}{a}}}{2}$$

$$= \sqrt{as}$$

where u_a is the average velocity, a is the acceleration due to the wind force, t is the time a water particle takes to cross the lake, and s is half the distance across the lake in the direction of the wind at point A. The amount of water arriving per unit time at any point on the downward shore will be:

$$t'\sqrt{as}$$

where t' is a dimension constant with a numerical value of one in the cgs system.

Since the amount of water arriving at a given point upon the downwind shore depends upon s in this way, the water will pile up to create a hydrostatic pressure difference between any two adjacent points, A, A', on the downwind side. The pressure gradient so set up will tend to accelerate the water over the interval $A.A'$ at a rate which will depend upon the steepness of the gradient and g, the acceleration due to gravity. That is,

$$\text{acceleration} = g\ \frac{d(t'\sqrt{as}}{dx}$$

where x is the distance of A from the center of the lake in a direction normal to the wind. Differentiating, we obtain

$$\frac{t'\sqrt{a}}{2\sqrt{s}}\ \frac{ds}{dx}$$

$$= \frac{t'x\sqrt{a},}{2s \cdot s}\quad \text{because } \frac{ds}{dx} = \frac{x}{s},\quad \text{the slope of the tangent at } A.$$

The acceleration producing a longshore current from A' to A will be greater near the ends of the lake than on the downwind side. As the current sweeps around the end of the lake, however, it will be flowing more and more against the wind force, which will tend to reduce it. This retardation depends upon the ratio between the component of the longshore velocity which is directly opposed to the wind force and the total longshore velocity, i.e., $\frac{s}{y}$, or $\frac{x}{r}$ in figure 2, and also upon the accelerating effect of the wind force in the following way:

$$\text{negative acceleration} = \frac{ax}{r}$$

The net acceleration, *N*, of the longshore current will be the difference between the accelerating and the retarding forces,

$$N = \frac{gt'x\sqrt{a}}{2s\sqrt{s}} - \frac{ax}{r}$$

$$= \frac{gt'\sqrt{r^2-s^2}\sqrt{a}}{2s\sqrt{s}} - \frac{a\sqrt{r^2-s^2}}{r}$$

It is possible for *s* to vary between zero and *r*. If we let it equal *r* as it does on the extreme downwind side of the lake, *N* becomes zero. If we let it equal zero, as it does at the ends of the lake, *N* becomes infinite.

Such an extreme value can never be obtained in nature, because of departures from geometrical circularity of the lake shape and the finite size of the moving parcels of water, but it is plain from the foregoing treatment that the acceleration, and hence the velocity, of the longshore currents is greater at the ends than elsewhere.

This theory of circulation is a first approximation only. It neglects several important considerations, notably eddy viscosity, depth of water, and variations of wind force over the surface of the lake. Of these factors, it seems likely that the first would decrease acceleration of the end rip currents, and the last two would increase it. Detailed analysis of these factors, and others, such as bottom roughness and Corioli's force, is beyond the scope of this paper, but it seems unlikely that anything beyond a quantitative change would be produced by them in a reasonably shallow lake. In lakes of over a few meters in depth it is probable that low-level return currents would have to be considered. Since the oriented lakes are very seldom more than 10 meters deep, and most are much shallower, it is very likely that they will obey the predictions of this theory rather closely.

The load which a current is competent to carry is dependent upon a power of its velocity, as is well known from studies of stream regimen, so the ends of the circular lake will tend to be scoured out by the longshore currents at a greater rate than the downwind shore, and the circular lake will gradually become elliptical or sub-elliptical, with its long axis at right angles to the prevailing wind.

Lakes whose bottom contours are visible from the air often show very good evidence of this scouring. Figure 3 shows sketch maps of lakes in the region around Teshekpuk Lake. It will be seen that there is, upon the downwind side of all these lakes, a very smooth, even, wave-action bench, which diminishes in width toward the ends of the lakes. In all lakes the bench is very narrow around the ends and in several there can be seen the marks of successive scours, which are no doubt the result of winds of different velocities. On the upwind side of the lakes there is another bench, even broader than the one on the downwind side. It is not so regular, however, and is cuspate in detail, just as one would expect of a bench which had been formed by deposition in a series of eddies.

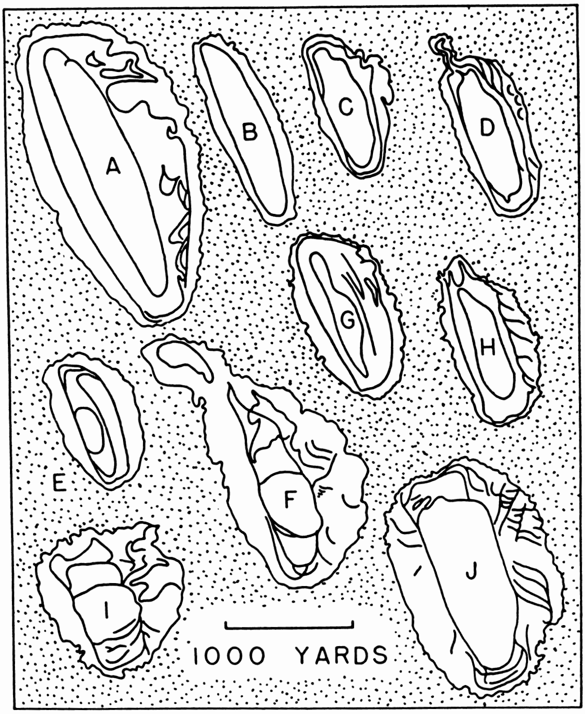

Fig. 3

These considerations provide an explanation for the orientation of the lakes and for the prevailing elliptical or sub-elliptical shape. It is not surprising that the lakes are seldom longer than the one shown in figure 3, B, for the wind of the Arctic Coastal Plain blows from a variety of directions other than the commonest northeasterly one. Other factors such as the finite size of moving water masses and the finite age of the lakes would limit the length of the basins even if the wind actually were constant in direction. It does not seem justifiable to state that the longest lake basins are the oldest, although they no doubt have a tendency, all other things being equal, to be older than the lakes of more nearly equiaxial elliptical shape.

It is difficult to see how the dynamics of erosion can be responsible for the sub-rectangular lakes which are found in some areas, but other explanations are usually available for these relatively scarce deviants from the usual shape. Black and Barksdale (1949) have shown that many of these lakes lie in rows behind raised strand lines, and in these the confining influence of the fossil beach bars may have squared off the basins. In other areas it is probable that longitudinal dunes act in the same way.

Other variations in the shape of oriented lakes are usually due to the complicated histories of individual basins. Coalition of neighboring basins, draining or partial draining and the influence of local topography all tend to vary shape, but it is not this variation which has been puzzling about the lakes of northern Alaska. The problem has been their general similarity, and this is fully understandable in the light of the postulated circulation system.

Since Alaskan lakes not only lie across the prevailing wind but were formed across it, some reconsideration must be given to the suggestion of Odum (1952) that the Carolina Bays were formed by a wind blowing parallel to their long axes. The Bays cannot have been excavated by such a wind while they were full of water, for then they would lie at right angles to their observed direction. If they were actually excavated by a wind from the direction his calculations suggest, then they must have been excavated as deflation basins during a period drier than the present. This is in full accord with his deduction (p. 269) that the relative humidity while the wind blew was low, and the precipitation less than it is today.

If the deductive approach used in this paper is valid, then the oriented lakes of Alaska are being excavated wet by winds which blow across them, and the Carolina Bays were excavated dry by a wind which blew along them.

Though these are the most spectacular fields of oriented lakes which are known, other fields occur elsewhere in the world. The largest, in northern Siberia, is probably of the same type as that in northern Alaska. The local fields which occur throughout the arid and semi-arid regions of the world, on the other hand, are almost certainly deflation basins. The large pans of the Lake Chrissie region, South Africa (Wellington, 1943), probably represent a special case, dominated by bedrock relief and an abandoned drainage channel.

It is very likely, though by no means certain, that orientation of lakes by end-current erosion is restricted to regions of perennially frozen ground. The fine-grained silts and sands of polar coastal plains, with their large included ice wedges, are peculiarly liable to attack by the combined action of waves and currents.

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