



On Sea-Beaches and Sandbanks

Author(s): Vaughan Cornish

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Spanish treachery at the San Juan de Ulua, an event which was long made puzzling and obscure by the blunders of his predecessors. But our gratitude is chiefly due to Mr. Corbett for showing that the 'Sir Francis Drake revived' is an authentic work, in spite of Mr. Froude's harsh and erroneous judgment. Mr. Corbett has found that the main statements contained in it are corroborated by Spanish reports. This is important, because 'Sir Francis Drake revived' is almost the sole authority for the most romantic part of the illustrious explorer's career. Mr. Corbett also clears up a great deal that was obscure in the Doughty business; and his arguments are quite conclusive respecting the discovery of the Cape Horn route. He very properly makes full use of the Zarate letter, which throws so much light on the internal economy of Drake's ship. We are indebted for the discovery of this letter, in the Seville Archives, to our good friend, Señor Peralta, who has also done so much excellent work connected with the history and anthropology of Central America.

Geographers will welcome the first volume of Mr. Corbett's important work as the best and most valuable biography of our illustrious circumnavigator, during the period that he was doing able and memorable service for geography.

The second volume is devoted to Sir Francis Drake's naval career, and here Mr. Corbett has done good service to the history of cartography, by the reproduction of the maps which were engraved to illustrate the 'Summary and True Discourse,' and of Adams's charts of the various actions in the channel with the Spanish fleet. The latter were published in the 'Discourse concerning the Spanish Fleet invading England' (1590), and are exceedingly interesting. Their execution reminds us of some of the work of engravers employed on Saxton's atlas, who were, no doubt, also employed to execute the Adams charts.

ON SEA-BEACHES AND SANDBANKS.*

By VAUGHAN CORNISH, M.Sc. (Vict. Univ.), F.C.S., F.R.G.S.

§ 1. SCOPE OF THE INVESTIGATION.

THIS paper is the sequel to one on "The Formation of Sand-dunes" in the *Geographical Journal*, March, 1897. It embodies a research upon the processes which distribute the detritus which enters the sea at its margin, and upon the behaviour of the material distributed. I have again given special attention to the peculiarities of mixed multitudes, some of which provided a key to much that was obscure in the behaviour of sand-dunes. As the research progresses this aspect of the phenomena acquires an increasing interest, and I hope to apply the results obtained in the study of dunes and beaches to other aggregates.

I have to acknowledge many valuable suggestions received during the preparation of the present paper from Dr. H. R. Mill, F.R.S.E., and Mr. Clement Reid, F.G.S.

* Paper read at the Royal Geographical Society, March 16, 1898.

I have also to thank Prof. G. H. Darwin, F.R.S., for information upon tides; Mr. F. E. Lacey, M.I.C.E., for the section of the Bournemouth beach; and Prof. J. Walther, of Jena, and Mr. W. Whitaker, F.R.S., for references to literature.

§ 2. THE MOTIONS OF THE BOTTOM WATER OF THE SEA.

(For Breakers, see § 5; and for further discussion of the Tides, see § 14.)

(a) CIRCULATION.—From the western tropical coasts of Africa and America the persistent south-east and north-east trade winds cause a surface drift towards the eastern coasts of America and Asia respectively. The southern is the watery hemisphere, and the shores of the Atlantic and of the Pacific converge in northern latitudes, the continents widening, and the oceans contracting. Wholly or partly on account of this circumstance, the surface drift of the south-east trades pours over into the region of the north-east trades, and the resulting surface drift of these co-operating winds is on the whole northerly—markedly so in the Atlantic. The waters of the Atlantic are piled up before the wind on the east coasts of the Americas, while under the west coast of Africa the water is constantly renewed, partly by coastal currents, and partly by a welling-up of water from below under the windward shore.* Such welling-up from below in off-shore winds has been repeatedly demonstrated by observations of saltness and temperature.† On the other hand, the driving of a surface current against a lee shore raises the level of the sea there to such an extent that gravity causes the lower layers of water, where the drag of the wind is slight, to flow back from the shore. Such is probably the cause of flow of the Gulf Stream in the earlier part of its course. This kind of reverse current may be compared to the effects of polarization in electrolytic phenomena. The great north-easterly drift across the Atlantic, which still goes by the name of Gulf Stream, is probably of mixed origin, being partly the reverse (polarization) current flowing on by its momentum, and partly a surface drift due to the south-westerly winds which prevail in these latitudes. Such surface drift before westerly winds, when piled up against the western shores of Europe, is capable of producing a reverse bottom current or undertow flowing off-shore.

When the area over which a wind acts is small relatively to the size of the sheet of water, or when a part of the water is sheltered, *e.g.* by a headland, the return current may principally flow by the side of the drift instead of underneath. There is, besides the polarization current due to gravity, a second sort of reverse current, *viz.* the *induction currents* (induced by viscosity), which, with eddies interposed as friction wheels, flow parallel with and in the opposite sense to the primary ocean currents.

The great drifts of surface water which flow from the more open to the narrower parts of the oceans, and from the southern and equatorial to the northern latitudes, are for the most part broad rivers between banks of water in the open ocean, whilst the induction currents which flow in the reverse sense often hug the shore. Here, therefore, as in the case of the polarization currents, *the motion which affects the sea bottom has the reverse direction to the main drift of the surface water.* In the case of along-shore winds, however, acting on the shallow water within the breaker-line, the bottom drag is in the direction of the wind, and there are other particular cases in which this is so (see § 8).

* See J. Y. Buchanan on "The Guinea and Equatorial Currents" (*Geographical Journal*, March, 1896).

† See, for example, F. L. Ekman on "The Causes of Ocean Currents" (Royal Soc. of Upsala, May 3^d, 1876); and H. R. Mill on "The Clyde Sea-area" (*Trans. Roy. Soc. Ed.*, vol. xxxvi.).

A river flowing into the sea as a surface current of light water creates an induction current* of sea-water which flows landwards under the outflowing water, so that in this case there is a bottom motion in a sense opposite to the surface current. Another important case is that illustrated by the exchange of waters between the Atlantic and the Mediterranean. There is a flow of surface water from the Atlantic to the Mediterranean, but evaporation has made the Mediterranean water salter and heavier than that of the Atlantic, and at greater depths the pressure of the Mediterranean column appears to be more than sufficient to counterbalance that of the column of Atlantic water. The bottom current flows from the enclosed sea towards the open ocean in a strong stream, the flow of which is perhaps assisted by an induction (as of rivers). In the North Sea, on the other hand, the waters of which are lighter than those of the Atlantic, the latter encroach or recede under the varying conditions; but it is important to note that an encroachment of Atlantic water, commencing as a surface drift, becomes an undercurrent by the gradual sinking of the heavier water, which pushes its way as a submerged wedge.† This is still more marked in the case of the encroachment of salter water into the Baltic. The lighter water escapes as a surface current.

From a region of cold and condensation (as the north polar sea), the outflowing water may escape in a current which extends from top to bottom of the sea, for the bottom layers are dense owing to the low temperature and concentration of salt, and the surface waters, although fresher, slope downwards towards the areas of evaporation.

The surface current of a *frozen* sea and the current of a debouching river are two cases in which the surface waters are directly concerned in the transport of detritus. The general character of the observed surface flow of oceanic water, as well as the observations of deep-sea temperature in equatorial regions, afford evidence of a slow creep of bottom water from the polar to the equatorial and trade-wind seas, where it ascends to supply the water lost by evaporation. From our present point of view (that of transport of marginal detritus) we are not much concerned to discriminate between water which flows to the pole as surface drift before the poleward winds and that which reaches the poles by distillation.

From the above considerations, it appears that, on the whole, *the quantity of motion of the bottom water of the sea is greater off-shore and oceanwards than in the reverse direction, especially within the limits where wave-action reaches the sea-bottom, but a local exception to this general rule occurs beneath those river waters which flow seawards as a surface current.*

It is solely for the sake of this proposition that the discussion of ocean currents has been introduced here; the author makes no claim to have added anything to the knowledge of ocean currents.

(b) THE OSCILLATION OF THE SEA. *Tides*.—The action of the sun and moon in creating tidal agitation is chiefly effective in the broad oceans, particularly in the encircling waters of the southern hemisphere. Tidal agitation in the narrow seas is chiefly due to the push originating in a difference of level, and transmitted by the agency of the Earth's gravity. Tidal agitation is supposed to be equal from the surface to the bottom, and to be transmitted as a "long wave" in which, practically, all the motion takes place in the direction of transmission, so that, except for the effects of friction and viscosity, the energy of each swing is perfectly transmitted. Thus the violence or intensity of the movement of water is increased in

* See, for example, the researches of Ekman, Mill, and Petterson.

† See H. N. Dickson, Reports, Fishery Board of Scotland.

proportion to the diminution of the quantity available for the transmission of this energy. Consequently, the oscillating currents become swifter where the waterway is contracted by converging coasts or by a submarine ledge.

Where the waterway is stopped, as for instance at the head of an inlet, the water continues to pile itself up against the coast until the *head* counterbalances the momentum of the oncoming current.* This piling up may cause an under-current off shore before the time of high tide. The waters of a bay at low tide are, however, often comparatively fresh, owing to the outletting of river waters; the incoming salter waters of the flood will therefore, in such cases, tend to burrow under in the form of a wedge, and the distribution of pressure may be such that, if water escapes during the incoming tide, it will rather be as a surface current.

The undisturbed run of a tidal current is a simple harmonic motion of twelve hours' period, but at any locality to which the tidal push is transmitted by two different paths, the movement of the waters is compounded of two simple harmonic motions of equal period, but generally differing in amplitude, and which may have any difference of phase. The most usual character of the resulting motion is rotation in an ellipse. Such rotation is produced where the straight run of the tides in a channel compounds with the on-and-off-shore swing in and out of a bay. The well-known longer-period oscillation combines in some localities to create a very great difference, and in others but a slight difference, to the range of the spring and neap tides respectively. The most rapid tidal currents run along shore (particularly off headlands), the on-and-off-shore currents being comparatively slow. The on-shore current during rising tide is generally more rapid than the off-shore current of the ebb, the latter lasting a longer time. The extreme case of this difference of intensity is reached in the bore of rivers.

To sum up, *the bottom agitation due to tides is greater near the shore, and in channels and in narrow seas, but probably extends, though with diminished force, to the bottom of the deep oceans. This variation of force as we proceed oceanwards is not, however, uniform, but is interrupted by nodes and loops* (see § 14).

Waves (outside the Breaker-line).—The oscillation of the water due to waves raised by wind decreases in geometrical progression as the depth below the surface increases in arithmetical progression (which is the usual law of decrease for cases of radiation), so that the agitation of even the largest recorded waves only disturbs the bottom water appreciably within a depth of about 150 fathoms. The movement of the surface water in a ground-swell is uniform rotation in a circle, which is equivalent to two equal harmonic motions, the first forwards and backwards in the direction in which the wave travels, the second an up-and-down motion. The forward motion takes place on the higher level, so that at each revolution half the energy of motion is transmitted forwards.† Not far from the bottom the motion corresponding to this surface movement is (nearly) a simple harmonic horizontal oscillation. The complicated movements quite close to a rough bottom are dealt with in the next subsection. When the swell reaches the shallows of the shore, the depth being small compared with the wave-length, it is easily observed that the front of the wave becomes steeper and the back flatter. In proportion as the form of the surface departs from the symmetrical curve of sines, which is the form of the ground-swell in deep water, so does the motion of the water near the bottom depart from the

* See, e.g., O. J. Lodge, Brit. Assoc., 'Handbook to Liverpool' (1896), p. 101.

† Osborne Reynolds, *Nature*, vol. xvi., 1877, p. 343: "On the Rate of Progression of Groups of Waves."

perfect balance of the harmonic oscillation. The forward motion is sharp and short, and the water is brought back to its former position by a slower motion lasting a longer time. The retardation of the wave-front in shallow water causes the swell to advance almost dead on shore; consequently the strongest oscillating bottom currents caused by the swell are on-and-off-shore, not along-shore, as in the case of the strongest tide-currents. It is to be noted that the bottom action of the waves becomes more intense the nearer we approach the shore. Again, since the depth to which wave-agitation extends depends primarily upon the wave-length, and only to a secondary degree upon the amplitude, long flat swells * (the dying waves of an ocean storm often almost invisible at sea) will stir the water at depths which would remain unaffected by high but short waves raised not far from the coast by an off-shore wind. Thus it is the oscillation due to the waves travelling shorewards which chiefly affects the motion of the water near the bottom. Similarly, the deeper waters of a channel (such as the English Channel) are more affected by a long swell from the ocean than by shorter waves running oceanwards from, e.g., the North Sea, even if the latter be somewhat higher.

If the margin of the sea be a cliff of rigid rock rising out of deep water, the energy transmitted shorewards by the swell is reflected back upon its path, and the difference of character between the on-shore and off-shore movement of the water is to a great extent obliterated, whilst the intensity of the agitation is increased.

To sum up, *the bottom oscillation of the sea due to the waves, decreases very rapidly from the shore seawards, and ceases altogether near the summit of the continental slope; near the coasts the oscillation is mainly on and-off shore, and the shoreward component of the oscillation is short and sharp, the seaward longer and slower.*

Seasonal Oscillation.—In addition to tides and waves, there is a third kind of periodical reversible disturbance to which the waters of the sea are subject, corresponding to the annual cycle of the seasons. This long-period disturbance superposes a noticeable twelve-monthly oscillation upon the circulation of some parts of the sea, e.g. in the regions of monsoons, and where the waters of the sea, or even those of the rivers only, freeze in winter.

(c) ON THE MOTION OF WATER NEAR A ROUGH BOTTOM.—When the velocity of a current is being retarded by the roughness of the bottom, bodies of swirling water continually rise from the bottom, especially from the lee side of obstructions. There is thus a constant upward motion of the bottom layer, *the buoyancy of which is increased, whilst its speed is diminished.*

The conditions where water is retarded by roughness of bottom are similar to those which obtain when a tidal current is gaining strength. In a succeeding portion with a smooth bottom there is a continuous settlement of water, and this corresponds to the conditions when tidal current is slackening. When the main body of water is agitated by an harmonic motion, such as nearly corresponds to the agitation communicated to the depths by the swell, the layer of water close to the rough bottom divides itself into regular segments, in which the water has alternately a motion with an upward component and a motion with a downward component; † in the latter the water settles, and in the former it is constantly pumped up, the balance being of course maintained by other currents. An important feature in the character of the bottom motion of water thus agitated is the high intensity momentarily obtained by the *upward* swirls. This is readily seen by the dance of the sand-grains when a glass trough containing water over a layer of sand is rocked to and fro.

* See Sir G. Stokes, 'Memorandum on Waves.'

† See G. H. Darwin, "On Ripple Mark" (*Proc. Roy. Soc.*, 1883).

§ 3. MUD FLATS OF THE DEEP SEA.

A regular oscillation or an indiscriminate agitation which rolls or drags a heavy body alternately uphill and downhill results in a downhill travel of the body, owing to the action of gravity. It is well known that mud travels persistently from the shore seawards, and that it forms the bottom over vast tracts beneath deep-sea water, *e.g.* at the foot of the continental slope, and in such positions as the depths of the Mediterranean, and the holes or pockets in the Baltic. Mud, however, settles with such extreme slowness, that wherever the bottom is disturbed by waves (say, to the edge of the continental shelf) it cannot anchor itself upon the bottom even during the slack water of the tides, so that the above-described action of gravity is effectually cheated. This leads to the conclusion that *the transit of mud down the slope from the shore is not due to the action of gravity*. That mud rests and accumulates at the foot of the continental slope, for instance, is due to the fact that the increased depth has removed the bottom from the disturbance of wave-action. Here at length gravity becomes effective, and brings down the mud. Were the waves of the sea to originate from the bottom, as do the standing waves of stony brooks, and to decrease in intensity towards the surface, gravity would oppose scarcely any resistance to the transport of the mud from the foot to the top even of the continental slope, and it would be in the still water on the top that the mud would settle. In like manner, the activity of a housemaid raises the dust from the floor of one's study to settle quietly upon the tops of pictures and bookcases.

It appears, then, that *the principal factor determining the well-known direction of mud-transport is the diminution of intensity of bottom agitation from the shallows to the depths*. The effects of diminishing intensity must be exemplified further in this place, for there are cases where the reverse effect is produced, the finest material seeking the positions of greatest agitation.* Such cases are the wake of dust which follows a railway train, and the cloud of lycopodium powder which, unable to disentangle itself from the swirling air above a metal plate which has been set in vibration, deposits at the positions where the agitation has been greatest. These are instances of agitation with intervals of complete quiescence. When, on the contrary (as *e.g.* within the limits of wave-action), the agitation is practically incessant, dust slowly shifts away from the area of agitation, as in the winnowing of chaff from a heap of grain.

The mud which is transported from the shore, and that which is produced on the bottom of the sea, is not restricted to a thin layer close to the bottom. Presumably, the sea within the area where wave-action extends to the bottom, bears throughout its whole depth, though in greatest quantity near the bottom, a haze of dancing dust such as a sunbeam reveals in the air. Conversely, the agitated water bearing this flying haze never covers a muddy bottom, except where the mud is being produced upon the spot, *e.g.* by the disintegration of a clayey rock; † or, occasionally, where water is stilled beneath an entanglement of waving seaweed.‡

The prevailing off-shore movement of the bottom water of the sea renders it probable that terrigenous mud is slowly transported oceanwards from the foot of the continental slope. The limit of transport is likely to be considerably beyond the limit to which the materials have been traced, for where the material is in but small proportion its presence is masked.

* See Faraday (*Phil. Trans.*, 1831) on "Acoustic Figures."

† See Delesse, 'Lithologie des Fonds des Mers,' p. 285.

‡ See Ch. Barrois in *An. Soc. Geol. du Nord*, t. xxiv., December 2, 1896, pp. 196, 197.

§ 4. THE SORTING OF SAND FROM SHINGLE AND FROM MUD.

Let the velocities of water required to move shingle (pebble) and sand be respectively—

Velocity for shingle (V_p)

Velocity for sand (V_s)

To fix our ideas, we may suppose for the moment that $V_p = 48$ inches per second, and $V_s = 12$ inches per second.* If we take a simultaneous view of the various modes of motion of the waters of the sea described in § 2, we shall see that *the usual condition of sea-water is one of oscillation* which is not quite symmetrical in amount (i.e. there is often a prevailing set in one direction), and *which is scarcely ever symmetrical in intensity, a short quick motion one way being balanced, as far as the movement of the water itself is concerned, by a long slow motion in the reverse direction.* Taking the later case, where there is no drift of the water, let the maximum shoreward velocity be V_p , and the maximum seaward velocity be V_s , then the sand will be moved to and fro, but the shingle will travel in one direction only, viz. shoreward, its progress being by a series of jerks.

If the duration of the backward swing at maximum velocity V_s be increased, so that there is a general drift of the water seaward, the sand will travel seaward, whilst the shingle continues to travel shoreward. Simultaneous transport in opposite directions is achieved without any drift of water when the sea-bottom slopes in the direction of the smaller velocity (in this case seaward). Shingle of 2 inches diameter sinks at the rate of about 24 inches per second, sand at about 2 inches per second. As, also, the shingle is generally only raised a small height from the bottom by the movement of the water, gravity has a much longer time to act on the sand. It follows that gravity has much more influence upon the rate of transport of sand than upon that of shingle. In the above case, the only effect of gravity on the motion of the shingle is to cause its (shoreward) path to be very slightly shorter. The sand, if the velocity of the onshore swing and the rate of reversal permit it to come to anchor between the two parts of the oscillation, will have its shoreward path appreciably shortened, and its seaward path appreciably lengthened. Thus *suitable oscillation on a seaward slope will set shingle travelling shoreward, and sand simultaneously travelling seaward.* If the velocity on the seaward half-swing of an oscillation be as great as V_p , the shingle is moved both ways, and is liable to travel seaward if the bottom slope from the shore.

The condition of the transport of shingle (great intensity of motion) keeps most of it close against the shore, often in a bank or beach; while the inability of mud to settle except where the water is quiet causes it, as we have seen, to accumulate in mud flats beyond the limits of wave-action. The accumulations of sand are of greater variety, for, although the mean term in size, it possesses a greater *independence of motion*, or persistence, or effective inertia, than either of the extreme terms. Mud (by which I intend throughout such characteristic marine mud as the well-known "blue mud") obeys each slightest swirl of the water; it follows almost exactly the stream-lines; and it is only in the slow settlement of the mud in still water that muddy water behaves otherwise than as an emulsion. Shingle, again, is not raised to any great height from the bottom, and sinks so swiftly that it does not take a long free flight in water. Hence, when it is moving it follows almost precisely the direction of the momentary movement of the water. Sand, on the other hand, is frequently churned up to a considerable height from the bottom, and

* See, for example, Wheeler, 'Tidal Rivers,' pp. 67, 68, quoting T. Logan for nearly similar figures. Also see Rankine, 'Manual of Civil Engineering' (1862), p. 708 (on the authority of Dubuat).

often has a long free path; and when the stream-lines of the water are suddenly deflected, whether vertically or horizontally, inertia carries the sand on, the stream lines of the sand being deflected less than those of the water. Similarly, when the current slackens the sand flings itself forwards, as is so noticeable in the rippling of sand by waves. *It is owing to its persistent motion that sea-sand accumulates in vast Banks where it is flung by the sudden bending or checking of currents (e.g. at tidal modes), or where it is dropped during tumultuous mixing of waters.*

§ 5. THE MAKING OF A SHINGLE BEACH.

(a) THE BREAKER.—If waves be transmitted without breaking (*e.g.* oily waves) towards a sloping shore formed of hard, impervious rock, the oily sea will wash up and down the slope of the shore between two lines, which are near the respective levels of the trough and the crest of the waves. If sand or pebble be placed upon the slope, this oscillation will enable gravity to bring such sand or pebble down to the foot of the slope. The wash of the sea is, however, complicated by the breaking of the wave. The water in the front of the breaker rises slowly. The water of the cusp, at the moment when it trembles to its fall, is moving somewhat rapidly forwards. The fall of the water is that of a body falling freely, and the downward velocity increases so that the last part of the fall of a large breaker is at a fairly high speed, probably not very different from what might be calculated in the ordinary way from the height of fall. The water is also moving forwards. The angle at which the water comes down varies according as the wind is off-shore (steeper), onshore (more sloping), and with other conditions. On a steep coast, this water often falls on the bare shore; it has then considerable power to push forward loose material. On a gently sloping shore, the breaker generally falls upon a cushion of water, which is, moreover, at this moment frequently moving seawards. The position of most intense motion in the breaker is usually not the falling front, but just behind, where, as the front falls, the water is swirled upward and forward with a surprising intensity of motion, which extends to the very bottom, and brings a rush of water over the fallen front. In point of fact, the breaker is usually, as it is sometimes called, a roller. In the transport of material, both the push of the fallen front and the jerk of the rising back act shoreward. That which we have just described is the whole of *the breaker proper*; *the bottom action is wholly shoreward*, and the intensity of motion which is attained at the critical moment is probably greater than any intensity of bottom motion attained in the sea except in tide-races.

(b) THE WASH OF THE WAVES.—The breaker flings and drives materials forward into the wash. On a sloping platform of impervious rock, the wash treats these materials as has been described above, *viz.* shakes them down again into the sea. The only marked difference is that occasionally the momentum of a flying pebble carries it further than the wash of the water. On the rocky platform at the base of a hard cliff, the boulders, when reduced to such size that the sea can roll them, are removed from the foreshore. This action is assisted at high tides by the resurging of the wash from the cliff foot.

Where the foreshore is composed of shingle, the proper work of the breaker continues as above, *viz.* the casting up of shingle, etc., for the wash to deal with; but the action of the wash is entirely different owing to *percolation*.* The rise and fall of water without breakers on a shingle beach would be simply a welling up and a sinking down through the shingle. But the advance of the sea upon the

* Compare A. R. Hunt, F.R.S., "On the Action of Waves on Sea-Beaches and Sea-Bottoms" (*Proc. Roy. Soc. Dublin*, vol. iv. part vi. p. 267).

beach taking place, not by the welling up of water, but by the discharge of a breaker, the on-wash runs over the surface of the beach, the water gradually filling up the interstices as it goes and *depositing its burden of shingle*, for, this being the same kind of material as that of which the beach is composed, the water cannot carry it down through the interstices. So much for what happens during rise of level. When the momentum of the on-wash is exhausted (the level of the sea at the breaker-line being also, as a rule, lowered so that the wash-water is no longer supported hydrostatically), the wash-water flows back in the following manner: viz. a considerable part sinks down through the shingle, and can thus no more carry back the new material from the surface than the liquid which trickles through any other filter can carry a precipitate with it; the remainder of the water runs back over the stony surface. The quantity of water flowing back over the surface being thus diminished by percolation, its impulse is correspondingly diminished, and the depth of the stream being decreased, the resistance of those pebbles which are not wholly immersed is greatly increased.

Thus the wash of the waves, owing to percolation, piles up the pebbles thrown forward by the breaker, forming a *bunk*, or *ridge*, or *Full*, and this is the action proper to the sea on a shore of shingle.

(c) THE SHINGLE *Full*.—The piling up of the ridge goes on, its height and steepness increasing, until the wash can reach no higher, and the steepness of the ridge at each point is such that the assistance which gravity gives to the down-flowing surface stream counterbalances the loss of transporting power due to percolation at that level.* This is the equilibrium profile or regimen of the *Full*. Now, the greater the volume of water flung forward by the breaker, the greater is the depth of the back-flowing surface stream, and thus for the same size of beach material the carrying power of the back-wash is more nearly equal to that of the on-wash. Consequently, in a given locality, the regimen slope of beach proper to a rough sea is not so steep as that for a quiet sea. Hence (partly) the common observation that the first effect of larger waves is to “cut into the beach,” an operation which consists in flattening and lengthening the slope of so much of the existing beach ridge, or *Full*, as the waves at the time are able to get at. If the stronger waves continue for a sufficient time, it will be found that their action is not different in kind from that of the gentler waves, for, after trimming down the seaward face of the old *Full*, they will proceed to construct a *Full* for themselves, at the top of which accumulation will proceed by percolation, until the *Full* has attained the maximum height to which the wash can reach. The sea face of this *Full* is longer and flatter than that given by a calmer sea. Practically, as heavy seas on our coasts do not continue for long, the equilibrium form due to such seas is comparatively seldom seen, and the initial stage of cutting into a steep beach-ridge is often mistaken for a real change from on-shore to off-shore action.

There is, however, a real removal of the beach by storms, as well as the mere temporary effect above described, due to the fact that the wind is more or less on-shore. The breaker is modified by the hurrying forward of the crest and by the undertow. The waves break further out, and the crest falls upon a cushion of water, and hence has less power to push shingle before it; the shoreward motion of the water at the foot of the falling breaker is less, or in extreme cases the motion

* Compare A. R. Hunt (*loc. cit.*), as follows: “It will be noted that the absorptive power of the shingle increases gradually from the margin of repose, where it is *nil*, owing to the shingle being saturated, to the point of furthest reach, where it may be perfect; and that absorption alone would suffice to account for a gradually increasing curve in the profile of a beach above the margin of repose.”

here may actually be seaward,* consequently less shingle is brought by the breaker than would otherwise be the case. These modifications diminish the amount of material deposited on the beach by the on-wash, whilst the work of the back-wash is assisted by the undertow.† As we proceed seaward the intensity of the bottom agitation diminishes, and at length the rate of the undertow, added to the rate due to the wave-motion propagated from the surface, no longer produces a seaward current equal to the critical velocity which we have called V_p , and the shingle gets no further seaward. Indeed, it seems that this action usually takes the shingle only a little way out, and that it is soon brought back again during off-shore winds, or even by the unaided operation of a moderate swell. Even in light on-shore wind, when the sea is only slightly agitated, shingle may be restored to the beach, for, the maximum velocity attained on the seaward swing of the wave just outside the breaker-line being less than the critical velocity V_p , the shingle will be fed into the breaker instead of being abstracted, and by it will be flung upon the beach.

When storms are accompanied by very high water (*e.g.* as with south-westerly winds in the English Channel at spring tides, or during north-westerly winds on the east coast of England), shingle in many localities may be removed from the beach whether the wind be somewhat on-shore, as in the former, or somewhat off-shore, as in the latter case. This is frequently due, not to the proper mode of action of the sea upon the shingle bottom, but to the circumstance that at such time the sea in many localities reaches some wall or obstruction from which the wash surges back. Where, however, there is no such obstruction to the proper action of the sea, much of the shingle removed from the seaward face of the shingle barrier is flung over the top, and the barrier is increased in height and pushed shorewards. In this way shingle swept from the foot of cliffs protects the neighbouring flat coasts.

(d) ON THE ACTION OF SEA DEFENCES UPON SHINGLE.—Although a natural barrier of shingle is capable of providing a defence against the flooding of low-lying land, this is conditional upon the shingle being free to travel shoreward in stormy weather. Moreover, at such times the erosion of the sea-bottom seaward of the beach, which is really a slow waste of the land, pushes landward the proper and stable position of the beach. Thus, unless shingle be supplied in such quantity as to produce a shingle Ness or foreland, the barrier is not fixed in position, although it be stable. Now, the first step taken in the “development” of an English watering-place on a lowlying coast, is usually the erection of a row of houses on the sea-front, with a parade abutting upon the beach. Thus having fixed for all time the line of the coast, the community is presently compelled to erect a sea-wall to stop the advance of the sea and its natural moving barrier of shingle. The consequence is, in many cases, that the beach, which contributes so much to the natural charm of the spot, is swept away by the back-wash from the wall, and the town is then situated on a small and mean artificial cliff, which is constantly being undermined. Unsightly groynes are then erected to hinder the removal of the shingle, and now it often becomes impossible even to take a walk upon the strand owing to the difference in level of the shingle on the two sides of the groynes, or, in other cases, owing to the groyne having failed altogether of its purpose, and having no bank of shingle against it on either side.

On a sandy coast, the consequences of building too close to the shore are scarcely

* See G. B. Airy, “Tides and Waves” (*Encycl. Metropolitana*).

† The backward wash is sometimes spoken of as “the undertow.” For distinctness it should be mentioned here that in what follows about undertow, I am referring to a seaward motion from the back of the breaker. Seaward motion on the land side of this I refer to as the backwash.

less disastrous to those natural beauties which are so important an element in the prosperity of a watering-place. As almost every promising spot on the English coasts is already either a watering-place or destined by the owners of land to become one, it may not be amiss to point out that a lengthened preservation of the present natural beauties is only to be attained by fixing the building front as far from the shore-line as is consistent with a good view of and ready access to the sea. Moreover, when a watering-place has developed into a populous and closely built town, the benefit of pure sea-air can only be obtained on the strip in front of the first-built row of houses. This strip should therefore be as wide as possible.

§ 6. ON THE RIDGE-AND-FURROW STRUCTURE OF A SHINGLE NESS.

Where the surplus income of shingle exceeds the loss by attrition, the shingle tract grows seaward. The surface of this tract is usually laid down in ridge and furrow ranged parallel to the sea-front. The greater the tidal range, and the more marked the difference between the levels reached at neap tide and at spring tide, the more distinctly will a seaward-growing beach show the ridge-and-furrow structure. Thus during neap tide there may be formed a *Full* so large that at the succeeding higher tides it is only rolled a short distance shorewards, not far enough to amalgamate it with the last spring tide *Full*. Similar conditions apply to the aggregated bank called the summer *Full*, and its amalgamation, or non-amalgamation, with the *Full* of the previous winter. The larger the *Full* the slower it travels; its condition of stability may be defined much in the same way as those of a desert dune. An embryo *Full*, as an embryo dune, may (1) be destroyed; (2) may be hurried into coalescence with an older, larger, and slower-moving *Full*; or (3) may in rare instances grow until it possesses the permanence and immobility which size alone can give to an aggregate of incoherent material. Thus, instead of coalescing, the larger *Fulls* remain isolated from one another, and we have the ridge-and-furrow structure (which is shown, *e.g.*, on the map of Dungeness, Sheet 4, Geological Survey, reproduced in Dr. Gulliver's paper in *Geographical Journal*, May, 1897, p. 541). It has been observed at Orford Ness,* and Dungeness, and at Langley Point,† that there is a rise in the level of the shingle towards the present shore-line. It is unnecessary to invoke upheaval or subsidence to account for such difference of level, for as a Ness grows out into the tideway it offers increased obstruction to the coastal currents, the momentum of which will consequently bank up the water to a higher level, and the elevation attained by successive *Fulls* will therefore continually increase.

§ 7. THE ALONG-SHORE DRIFT OF BEACH SHINGLE.

(a) THE ACTION OF OBLIQUE BREAKERS.—On a steep shore, obliquely running waves break before they have time to swing round so as completely to face the shore, so that along-shore wind gives obliquely acting breakers. On a gently sloping shore, and with an ocean swell, the wave swings round almost parallel to the shore before breaking, and the line of action is therefore at right angles to the shore, or nearly so. But although one wave cannot give a very oblique breaker on a shallow shore, *two* waves can. With the wind along-shore there are generally two principal sets of waves running, viz. the set which runs straight for the shore, coming in from the offing, and the set which travels nearly parallel to the shore, running before the wind. In deep water the waves of these two sets pass through each other, their interference being momentary

* Redman, *Min. Proc. Inst. C.E.*, 1865, vol. 23.

† Topley, 'Mem. Geol. Survey,' Weald, p. 314.

and not in any way hindering the transmission by each of its proper impulse in the direct line of its motion. But the depth in which water breaks depends upon the height of the billow; consequently, when these two sets of waves are running, the combined billow formed by the coincidence of the two crests breaks before the time proper to the along-shore wave, and therefore before it can swing round to face the shore. The depths in the combined troughs being correspondingly diminished, the water there does not break. At the moment of breaking of the combined crests, the water simultaneously receives two impulses, one directly on-shore, and the other very oblique to the shore. There is no longer sufficient depth of water in front to transmit these two impulses, and instead there is a projection of the water in the direction of their mechanical resultant. The result is the rapid succession of the *short breaker* in the direction shown in Fig. 1. Under a sheltering headland the lateral waves which run before the wind are small, and only serve to serrate the crest of the wave which comes from the offing.

(b) THE DRAG OF THE WIND.—The drag exercised by wind upon the sea bottom is nowhere else so strong as in the shallow wash of the waves* with a breeze blowing along-shore, where its power is beautifully illustrated by the rippling of the froth which floats within the breaker-line. The swing given by wind to the water of the wash is easily seen. The bottom drag of the along-shore wind is also considerable at the small depth where the waves break. Here incessant agitation keeps the shingle constantly on the move, buoyed by upward swirls, so that the drift of the water before the wind can influence its motion.

(c) WIND CO-OPERATING WITH CHANGE OF SEA-LEVEL.—It is evident that the greatest amount of transport can occur when the sea acts upon the greatest quantity of shingle—that is to say, when the sea is at its highest level. The transporting power increases in a more rapid ratio than the rise of level, owing to the circumstance that most of the shingle is accumulated on the landward side of the beach, where its thickness is greatest. It follows that a wind blowing in the direction of the flood tide will have an advantage in shingle-transport over the wind which blows with the ebb, for the former, by opposing the turn of the tide, tends to increase the duration of tidal high water, and to diminish the duration of tidal low water. Thus, although the forces of currents may be equal and opposite in the two cases,

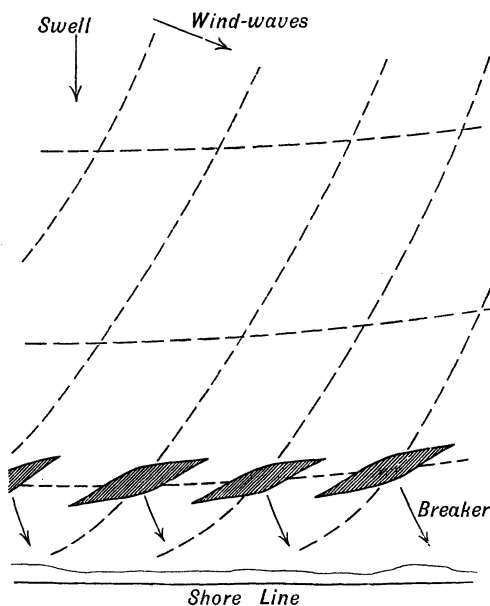


FIG. 1.—WAVES COMPOUNDING TO FORM OBLIQUE BREAKERS.

* Compare remarks by Sir George Nares, *Min. Proc. Inst. C.E.*, cxxv., 1895-6, pt. iii. p. 36.

the opportunities of action on shingle are greater when the wind blows with the flood tide. Again, the waves break most violently on the steep beach near high-tide mark, which further increases the effect of prolonged high water in promoting transport. The along-shore wind which is accompanied by a low barometer has a corresponding advantage of opportunity over the along-shore wind which is accompanied by a high barometer, and the wind along-shore which blows from the greater expanse of water over the wind which blows from the less.

It is necessary to guard against the assumption that the greatest amount of shingle transport is, at every point of the coast, in the direction of action of the more potent forces. For let us consider the case where a beach receives a large supply of detritus of a certain kind at, say, the north end, and a small supply of the same kind of detritus at the south end. Between these ends the tide ebbs and flows, and the winds are sometimes north and sometimes south. Let the forces acting from the south be slightly the more potent; then, *since the difference of forces is small and the difference of quantities is great, there may be a greater transport in the direction of action of the smaller force, since the motion of the water is oscillatory.*

(d) SHINGLE SPITS.—The along-shore drift of beach shingle often extends a shore beach as a shingle spit projecting between sea and calm water at the entrance of rivers and estuaries. The permanence of these spits may well excite surprise, considering their apparent liability to be swept bodily away. Their safety is in the opportunity they enjoy of receding before a storm, the shingle being pushed by the percolating water,* and material scoured from the face being flung over to the back of the bank into still water, whence it does not return. The velocity of the tidal currents at the point continually increases as the spit lengthens. The flood-tide (coming from the quarter which brings waves) is, from this circumstance, much the more effective in moving shingle, hence the curvature increases near the end of the spit. The curvature of the stream-lines at the end of the spit has practically no effect during ebb-tide, for it is against the waves.

§ 8. ON THE TRAVEL OF SHINGLE ACROSS THE BAYS OF THE ENGLISH CHANNEL.

The velocity of tide currents in the bays of the English Channel † is in many cases insufficient to make shingle shift; but, as Sir George Stokes has shown,‡ the tidal current in co-operation with the long Atlantic swell is sufficient to move shingle at a depth even greater than is attained in these bays. Therefore, with such a swell running, the shingle in the bays will travel backwards and forwards with the tide; but during winds from the Atlantic, there is a flow of water through the English Channel from west to east,§ and the bottom current must be in this direction, for the wind blows from the saltier to the fresher water. When the west wind subsides, an equal, or perhaps a smaller, quantity of water finds its way back down channel; but the waves have now subsided, the bottom water is therefore but slightly agitated in the deeper parts of the bays, and consequently the shingle does not travel westwards. The waves from the east in the English Channel are, it is generally allowed, of less amplitude than those from the west, and, which is of more importance, they are of much smaller wave-length. From such data as

* This action is very marked in the case of the Chesil beach, and (as has been pointed out to me) aids the encroachment of the Fleet upon the opposite shore.

† Consult, for instance, King's 'Pilots' Handbook for the English Channel,' 12th edition, revised by Commander T. A. Hull.

‡ *Trans. Devon. Assoc.*, vol. xix. pp. 512–515.

§ Compare Mr. H. N. Dickson's salinity maps in *Geographical Journal*, March, 1896.

I have, I reckon that they would move shingle at 10 fathoms, hardly at all at 20 fathoms, and probably not at 30 fathoms, which is about the greatest depth in these bays. But even at 10 fathoms, the movement of shingle must be little more than an oscillation with the tide, for there can be but little bottom drag in the direction of a wind blowing off the continent from fresher towards saltier water. I conclude, therefore, that the shingle swept past the headlands of our south coast can work its way, in the course of the seasons, eastwards across the bays. When in this manner it is once more brought to shallow water, the sharper shoreward impulse of the swell which has "felt the bottom" jerks it in, until it once more reaches the breaker and is thrown upon the beach.

§ 9. ON THE GROWTH AND DIMINUTION OF A SHINGLE NESS.

The coast-line recedes before the sea at any part (not suffering upheaval) where the removal of detritus (by littoral drift and off-shore movement) is not compensated by an equal or greater amount brought by the sea. The direct local supply of detritus, by waste of the coast, obviously cannot cause that part of the coast to advance. Shingle is chiefly derived from the waste of cliffs;* under cliffs of compact rock littoral drift is accelerated, and shingle beaches form to "leeward." At any part of a shingly shore where supply exceeds loss (e.g. on account of checking of current), the beach grows seaward. This increases the total length of the shingly coast, and the supply of shingle per yard frontage therefore decreases, until it only just suffices to compensate the loss. The Ness has then reached its maximum growth under the given conditions. Such growth may commence, for instance, when a wasting chalk hill slopes seawards, so that the height of the cliff and the supply of flints which feeds the beach are increasing. Conversely, the Ness may diminish when the receding hill which supplies it slopes landwards. Dungeness is supplied, not directly from the waste of cliffs, but indirectly through an intermediate deposit which encratches, after the manner described under "Shingle Spits," upon the river Rother. The point of Dungeness tends, therefore, to preserve a constant bearing and distance from the extremity of this accumulation of shingle, and therefore, of necessity, a constant distance and bearing from the mouth of the Rother, the position of which is controlled by that of the shingle bank to the westward. An accumulation such as Dungeness is less subject to alternate growth and diminution than a Ness which is fed directly from a wasting cliff, for the annual supply depends upon the outgoings from the intermediate store-house for shingle. This is determined by the length of its sea-front, which is not appreciably affected by the removal of several layers of the shingle. Thus the fluctuations of the cliff-supply are diminished.

§ 10. THE GRADING OF BEACH SHINGLE.

(a) THE LAWS OF THE GRADING OF BEACH SHINGLE.—No stony particle of less than a certain critical size can remain permanently on a beach, but is ultimately swept out to sea. This critical size is greater on a coarse-grained than on a fine-grained beach, for the *regimen* slope of the former is steeper, and gravity therefore gives greater assistance to the back-wash. It is well known that every particle upon the surface of a beach suffers attrition, whence the conclusion has been too hastily drawn that the grain of an isolated beach naturally becomes finer as the distance increases from the extremity where the beach is fed with detritus. Now, it is to be noted that *whereas the attrition of the particles tends to lower the average size of the shingle, and hence to make the grain of the beach finer, the removal of particles of less than the critical size raises the average dimension of the shingle.* Hence we may

* Except where mountain torrents rush straight to sea, as, e.g., on the Riviera.

deduce the following laws of grading of beach shingle applicable to a beach fed entirely at one extremity, whence the material travels along the beach :—

Law 1. If the material be of uniform size, the grain of the beach becomes finer as we recede from the source of supply.

Law 2. If the material be mostly fine stuff, with a small admixture of coarse stuff, then (unless the coarse stuff be very friable, and the fine stuff very durable) the grain of the beach will become coarser as we recede from the source of supply, for the average size is more affected by the removal of a large number of fine grains than by the attrition of a small number of coarse grains. This increase in coarseness will continue until the beach material is brought to a uniform size, when the grading proceeds as in 1.

Law 3. If the material be mostly coarse stuff, with a small admixture of fine stuff, then, as we recede from the source of supply, the grain of the beach will become finer, for the attrition of a great number of large particles has a greater effect upon the average size of the material than the removal of a small number of fine particles.

By combining 2 and 3 we can deduce the following corollaries applicable to a beach fed from both extremities :—

Cor. i. If the material fed in at one extremity be mostly fine, and at the other mostly coarse, the grain of the beach increases in size from the former to the latter extremity, the two modes of grading co-operating.

Cor. ii. If the material fed in at both extremities be mostly fine, the grain of the beach will be coarser in the middle.

Cor. iii. If the material fed in at both extremities be mostly coarse, the grain of the beach will be finer in the middle.

Law 4. The grain of the beach is (*ceteris paribus*) coarser where the beach is exposed to the heaviest breakers. This law follows from what has been said on the action of the back-wash, and on a “critical size” of beach material. We may add to the italics of § 5 (c) that the deeper back-flowing stream floats out the smaller shingle.

Law 5. The grain of the beach is (*ceteris paribus*) coarser near the “weather” end of a promontory. Thus, if west be the weather side, and the end of a long beach be protected from the east by a headland at the eastern extremity, then both large and small pebbles will travel eastward along the beach in a westerly wind, but only the small ones are carried back from the promontory during an east wind, so that the proportion of large pebbles to small is increased as we near the promontory from the west. This is, in fact, similar to the case of the sorting of sand from shingle by unsymmetrical oscillation, as described in § 4.

Grading by Groynes.—When groynes are erected to check the drift of shingle, we find that the shingle is coarse where it is piled up near the seaward extremity or point of each groyne (A, A', A'', Fig. 2), and relatively fine at the base of the groynes (B, B', B''). This grading is effected as follows: At the points (A) the breakers beat most strongly, and from these positions the next step in advance can only be made by sweeping out shingle round the end of the groyne; thus, as we go from the A to the B positions, the ratio of the rate of removal of fine shingle to the rate of removal of coarse shingle increases, the proportion of coarse shingle present is therefore correspondingly increased at the A positions, and the grain of the beach at these positions is consequently large.

(b) ON THE DIFFUSIBILITY OF SHINGLE.—It appears that the grading of shingle and the phenomena of long-shore drift of shingle must of necessity be influenced by a peculiar process, which, from its physical analogies, I term a process of diffusion.

In virtue of the property termed “diffusibility,” the particles of contiguous masses

of liquids or gas intermix somewhat slowly, not only without the assistance of external agency, but even against such agency, the process being termed "diffusion." If an aggregate of stones be exposed to an *absolutely steady current*, there is no motion of individual particles up-stream, but *when, as is usual on beaches, the main drift of the material is in the direction of the more potent of two alternating motions of water, there may be a true diffusion of shingle against the drift.* In order to fix our ideas, let us suppose that the main drift due to the motion of the water is eastwards. Now, since it is only the top layers of a beach which move, such shingle as happens at any time to be buried escapes transport until again uncovered. *Among an indefinitely large number of cases, it must happen that some pebbles driven westwards are always buried when the easterly drift succeeds, and are uncovered during the next westerly drift, and hence go westwards again, working their way against the main drift.* The chances are against any selected pebble working its way against the drift, and experiments with a moderate number of selected pebbles

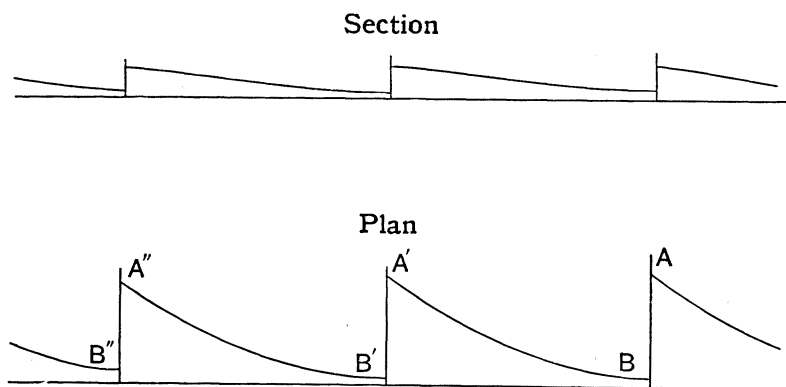


FIG. 2.—GRADING BY GROYNES.

ought therefore, as a rule, to yield negative results, but with the very large numbers of particles which are supplied naturally to a beach by denudation, some are sure to go against the drift. Now, the study of clastic aggregates such as beaches differs from that of gases or of liquids, in that the molecule or wandering individual of beaches *can* be perceived. Clerk Maxwell has pointed out that deductions from the statistical study of gases might not apply to the behaviour of those individual molecules which sharpened faculties would enable a man to study. Conversely, if we recognize one or two travelled pebbles of a conspicuous kind, we must not straightway conclude that the main drift of the shingle is from the direction whence these pebbles come. Due account must be taken of diffusibility.

(c) A BEACH SURVEY.—What is now wanted for the further study of grading and drift of shingle and sand, is a simultaneous survey of a complete coast-line, preferably the whole coast-line of Great Britain. The samples should be collected between the high tides of the same day, and should be taken just below the last high-water mark. If practicable, the survey should be made in duplicate at six months' interval. The Coastguard provides the requisite organization; the cost and trouble would be but small if the Admiralty give the order. In addition to serving the special purpose which I have indicated, the collection would be a permanent work of reference for the geologist and the civil engineer.

(To be continued.)