The Ecology of Lagos Lagoon. V. Some Physical Properties of Lagoon Deposits

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THE ECOLOGY OF LAGOS LAGOON
V. SOME PHYSICAL PROPERTIES OF LAGOON DEPOSITS

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(Plates 15 to 17)

This investigation is an attempt to discover the ways in which differences in composition of natural sand deposits may limit the distribution of burrowing animals by affecting first the volume of water a given weight of sand will contain, and secondly, the freedom with which water will flow between the grains.

The geometrical arrangement of systems of closely packed spheres is considered.

Measurements of porosity have been made first on different sand fractions prepared by sieving, then on various mixtures of these fractions and, finally, on a number of natural sands of known composition. The relation between porosity and composition in sands is discussed.

The extent of the capillary lift in various grades of sand has been studied and the instability of quicksands associated with the volume of capillary water held against gravity relative to the water required to saturate the sand.

From differences observed in the rate of evaporation of water from sands, an estimate is made of the percentage of water held by surface forces in the finer interstices of different sand fractions.

A method is described for determining the rate of drainage of water through a standard sand column as a measure of permeability. The effect of different quantities of fine sand and silt on the permeability of natural sand deposits has been studied.

It is shown that the depth at which blackening occurs in tropical lagoon sands is directly related to the rate of drainage, and provides a convenient method whereby permeability can be estimated in the field.

A new scale of sieves is recommended for the analysis of sand samples.

It is noted that the occurrence of lancelets in the lagoon sand deposits is related to the stability of the sand and to its permeability.

INTRODUCTION

An investigation into the factors governing the distribution of lancelets in the brackish lagoons and creeks surrounding Lagos has shown that lancelets were repelled by deposits containing fine sand passing a 90-mesh to the inch sieve in excess of 25 % or silt in excess of 1·5 % (see part IV). It was suggested that the suitability of the sand for lancelets depends upon its physical properties which change with the addition of fine particles. This study of the physical properties of lagoon sands was undertaken to show how changes in the composition of sand might limit the distribution of burrowing animals.

Very little work has been done bearing directly on either the relation of animals to different sands or the properties of marine or lagoon sands necessary for the support of animal life. Reid (1930) found that the addition of 2·0 % of various finely divided materials such as amorphous ferric-oxide and kaolin rendered sand unsuitable for *Arenicola*, presumably because the physical properties of the sand had been altered. Beanland (1940), in a paper on the sand and mud community in the Dovey Estuary, also related the fauna to soil texture and showed that different communities are found in different soils. A similar survey of sand and mud banks in the Exe Estuary was made by Holme (1949), who suggested that the occurrence and density of many of the species is related to the silt content of the soil or some factor connected with it. He also emphasized that soil drainage is of importance in determining the distribution of animals, but he did not relate drainage rates to the distribution of specific animals. A marine ecologist surveying the intertidal region can frequently, by inspection of the sand, indicate from experience the species likely to be found in sand of a certain texture, but he would have difficulty in tabulating the characteristics which led to the diagnosis. In spite of the complexity of sand deposits, it seems probable that quite simple differences in their physical characteristics are responsible for the fact that some burrowing animals colonize certain sands in preference to others. These differences appear to be related to texture and must be such as will affect the reactions of sand-dwelling animals. It should be possible, therefore, to correlate differences in texture with changes in those physical properties on which the fulfilment of the requirements of burrowing animals depends.

Bruce (1928) discussed the physical factors of a sandy beach and made important observations on the texture of a sand and its contained water, but did not relate his findings to distribution of the sand fauna. Chapman & Newell (1947) considered that the property of thixotropy in a sand is important to the burrowing activities of *Arenicola*. Chapman (1949) also studied the phenomena of both thixotropy and dilatancy in marine soils and discussed the change in physical properties occurring when different amounts of water are added to sand. He concluded that the fluidity or otherwise of a marine soil is a function of the viscosity and density of the liquid filling the interstices between the particles. Again his findings were not specifically related to animal distribution. It appears, therefore, that there are still insufficient data both on the properties of sand and on the distribution of most sand-dwelling animals to show how sand texture may impose limitations on the spread of different species. However, the studies that have been made on the distribution and reactions of the lancelet, *Branchiostoma nigeriense* (see part IV), are such that, if the physical properties of sand responsible for the distribution of that animal can be determined, an indication of the relation between sand texture and the occurrence of other burrowing forms may also be found.

Sands are, perhaps, the most varied of all deposits and, as their properties depend on both the proportions and spatial relations of the different sizes of grain and the extent of the microfauna and microflora they support, any disturbance of the natural deposit is liable to change its characteristics. Thus the removal of a sample from its bed alters the packing of the grains and further treatment such as drying or sieving may destroy the living component. Any experiment with sand, therefore, that is not carried out *in situ* is open to the criticism that the results may not apply to the undisturbed deposit. For these reasons, and also because no two sands are exactly alike, an investigation of the physical properties of sands at the best can only produce results which are an approximation. In the present paper attention is given mainly to the factors determining the volume of water which can be held in the interstices in different sands and the freedom with which that water will circulate between the grains. It is believed that differences with regard to these features are important in limiting the distribution of lancelets and perhaps also of other animals with similar modes of life. By altering the composition of sands with known properties and measuring the extent to which the properties have changed, an attempt has been made to arrive at some of the basic principles on which the physical characteristics of sands depend.

The porosity of sands

It seemed probable that the suitability of a sand deposit for colonization by burrowing animals might depend in part on its porosity, that is the volume of the spaces between the grains relative to the volume of the sand itself. Bruce (1928) pointed out that, in a system of uniform spheres, the volume of the interstitial space was 25·96 % of the total volume of the system irrespective of the size of the spheres. Graton & Frazer (1935) also studied the porosity of aggregates of systematically packed uniform spheres and found that various geometrical arrangements of the spheres are possible giving rise to both a number of different types of regularly arranged interstitial spaces and also to more or less irregular arcades. They estimated that, according to the type of geometrical arrangement, theoretical values for porosity varying from 26 to 49 % are possible. The theoretical figure used by Bruce, therefore, was that for the closest packing.

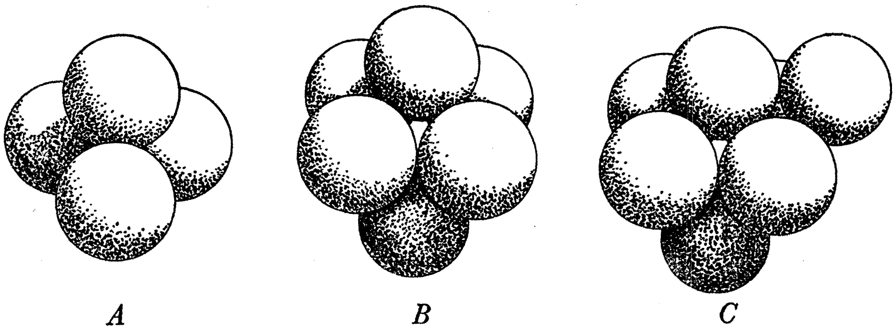

Figure 1. Diagram showing the unit arrangements of spheres basic to a system of closely packed spheres of uniform size. *A*, four spheres enclosing a curvilinear tetrahedron of void; *B*, six spheres enclosing a curvilinear cube of void; *C*, a system of seven spheres combining both the tetrad and six sphere units.

In a system of closely packed spheres of uniform size the unit arrangements of spheres are of two kinds, alternating one with the other. The first consists of four spheres, the centres of which form a tetrahedron (figure 1*A*); the second consists of six spheres, four of which are equatorial with their centres at the corners of a square while the remaining two rest above and beneath and thus may be considered as polar (figure 1*B*), the centres of the spheres in this unit forming a double pyramid with a square base and all of its sides of length twice the radius of a sphere. These two unit arrangements share common spheres so that the addition of one sphere touching any three of the unit of six gives a system of seven spheres which is a combination of both (figure 1*C*). By the addition of other spheres these units are repeated and will form a close-packed system of infinite extent. The interstitial spaces of the two basic unit arrangements are not the same. The tetrad of spheres encloses a curvilinear tetrahedron of void which would contain a small sphere of radius 0·225a touching all four large spheres, where a is the radius of the large spheres. The unit of six spheres, on the other hand, encloses a curvilinear cube of void which would contain a sphere of intermediate radius 0·414a. Assuming that the system of large spheres is an infinite lattice and thus ignoring edge effects, the total number of interstices is twice the number of large spheres. One half of these are curvilinear tetrahedra and the other half curvilinear cubes. If small spheres of the two sizes in sufficient numbers to occupy all these spaces are inserted between the large spheres, then the volume of spheres in the system is increased by 8·23 % and porosity correspondingly reduced by 23·4 %, the spatial arrangements of the large spheres being undisturbed. If, however, the intermediate-sized spheres become lodged within the tetrahedra and the small spheres within the cubical voids, each unit of four large spheres will be expanded by the insertion of a sphere too large for the cavity between them, while the cubical voids, if they had been unaffected by this disorganization, would contain eight small spheres of total volume about one and one-third that of one intermediate sphere. This rearrangement not only causes an expansion of the lattice, but also leaves some of the original cubical spaces unoccupied. Under these circumstances the porosity of the system would rise considerably above that of the close-packed uniform spheres. The extent of the rise or fall in porosity following the addition of small and intermediate spheres would be governed by their distribution and should approximate in a random mixture to the mean of the maximum and minimum porosities possible from discordant and harmonious packing respectively.

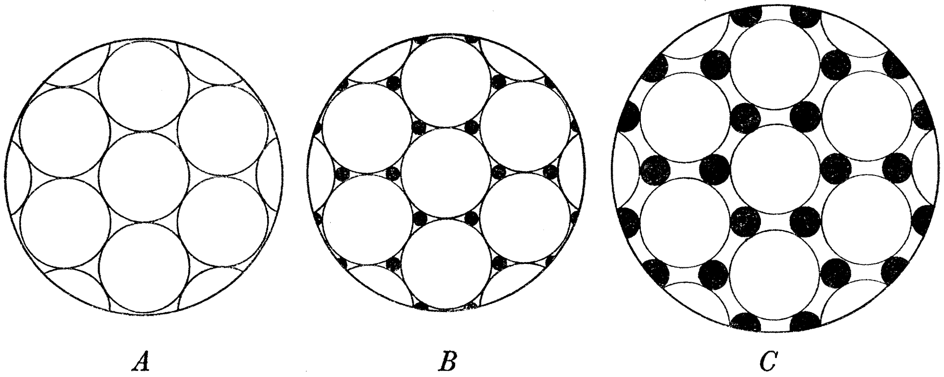

FIGURE 2. Diagram illustrating the effects of introducing small spherical particles into a system of closely packed uniform spheres. *A*, a closely packed system of uniform spheres; *B*, the system after introduction of spheres $\frac{1}{5}$th to $\frac{1}{6}$th the diameter of the large spheres resulting in a reduction in porosity. *C*, the system after introduction of spheres $\frac{1}{3}$rd the diameter of the large spheres resulting in an increase in porosity.

The effect on porosity of insertion of small or medium-sized spheres into a system of uniform large spheres is also demonstrated in figure 2, although these diagrams, being two-dimensional, do not show the existence of the two types of interstitial space which do not occur in the same plane. In figure 2*A* a system of uniform spheres is represented between which small spheres one-sixth their radius can be inserted, as in figure 2*B*, with corresponding reduction in porosity. If these small spheres are replaced by others of one-third the radius of the large spheres, as in figure 2*C*, the lattice of the system is expanded and there is a very considerable increase in porosity. If spheres of radius 0·225a only are added to the uniform system of spheres of radius a as in figure 2*B*, then the system will contain nine times as many small spheres as large without disturbance of the lattice. The addition of this number of small spheres represents an increase in the total volume of spheres by 10·25 % and a corresponding reduction in porosity by 28·5 %.

Sands are not uniform, the grains are not spherical and they are not arranged to give the closest possible packing. Nevertheless, an interpretation of sand in terms of systems of spheres is a valuable aid to the appreciation of the geometrical possibilities of other particulate systems and is a guide to the types of packing which may arise when sand grains of different sizes are mixed. As packing in sands is largely haphazard, the only indication of the arrangement of the grains lies in the variations in porosity. Gaither (1953) concluded that natural sands should have a porosity of about 37 %, but this is clearly not always the case, for Bruce (1928) has shown that the porosity of an ungraded Port Erin sand from the Isle of Man is 20 %, while in graded fractions of that sand porosity was as high as 44·7 %.

The method used by Bruce (1928) for measuring porosity in sands compared the volume of water saturating a sand with the volume of the wet sand. In calculating porosity volumetrically not only is it difficult to obtain an accurate measurement of the volume of a mass of wet sand, but, in similar volumes of different sands, both the weight of sand and the weight of water vary and the only figure available for direct comparison is the ratio between them. A more accurate estimation is possible if porosity is determined as the weight of water needed to saturate a given weight of dry sand. As the weight of the sand is fixed the volume of the wet sand differs from sample to sample. Thus changes in the weight of water to saturate different mixtures is equivalent to the expansion or contraction of the lattice formed by a given weight of sand grains according to the sizes of grains mixed and their spatial arrangement. In this method both the weight of sand and the weight of water are strictly comparable from test to test, while the volumes of sand and water can be calculated if their specific gravities are known. In the case of the West African lagoon sands the grains are almost entirely of quartz, the proportions of other minerals present being very small. As the specific gravity of quartz is 2·65, the volume of the grains in 100 g dry sand can be assumed to be 37·5 to 37·7 cm^3, a figure which has been checked by direct measurement. In this study, porosity was taken as the weight of water at a temperature of 25 to 30 °C required to saturate 100 g of sand in which the grains did not cohere. It has been found essential to use this method if small differences and variations in interstitial volume which might be important to burrowing animals are to be appreciated.

It is clear from hypothetical systems of spheres that porosity in sands will vary according to both the different sizes of grains present and their shape. Sands consist of grains usually within a continuous range of grain size, but differ in the extent of that range and in the points at which the modes of distribution of grain size fall within the range. In analyzing a sand by sieving, the range of grains of different sizes is divided somewhat arbitrarily into sections and the weight of grains falling into each is compared. The lagoon sands of Lagos mostly range in size of quartz particle from 2·0 to 0·1 mm in diameter. This range has been divided into four grades—2·0 to 0·6 mm, 0·6 to 0·3 mm, 0·3 to 0·2 mm and 0·2 to 0·1 mm—by using sieves of 30-, 60- and 90-mesh to the inch. The grades are referred to as >30, 30–60, 60–90 and <90 grades respectively from the sieve sizes separating them.

In determining the shape of the grains, Russell & Taylor's (1937) classification of roundness value in sand grains, in which the following five categories are recognized, has been used:

Angular. Grains with little or no evidence of wear, e.g. sharp edges and corners present.

Subangular. Grains with the edges and corners rounded.

Subrounded. Grains with the edges and corners rounded to smooth curves, but the original shape of the grain is still distinct.

Rounded. Grains with the original faces almost destroyed. Some comparatively flat surfaces may be present and also some re-entrant angles.

Well-rounded. Grains in which the entire surface consists of broad curves and no original faces are left.

On the basis of this classification it is seen from the photographs showing the size, uniformity and shape of lagoon sand grains in plates 15 and 16, that the > 30 grains are rounded and the 60–90 grains subrounded, but that the 30–60 and the < 90 grains are subangular. It has already been remarked (see part I) that these lagoon sand grains show signs of wind etching and are in general more rounded than the riverine sands from that area.

The porosity of graded sands

The porosity of the four grades of sand of different range of grain size prepared by sieving through the 30-, 60- and 90-mesh to the inch sieves was determined by weighing the water needed to saturate 100 g dry sand. The interstitial space expressed as a percentage of the total volume of wet sand was also calculated for comparison with these figures. These results are given in table 1.

TABLE 1

grade of sand (mesh/in.)	range of grain size (mm)	weight of water to saturate 100 g of dry sand (g)	interstitial space as % of total volume of wet sand (%)	ratio between diameters of smallest and largest grains	grain shape
> 30	2·0–0·6	23·2	38·0	1:3	rounded
30–60	0·6–0·3	22·5	37·0	1:2	subangular
60–90	0·3–0·2	24·5	39·5	1:1·5	subrounded
< 90	0·2–0·1	23·5	38·5	1:2	subangular
above grades mixed in equal parts	2·0–0·1	16·6	30·5	1:20	mixed

The figures in table 1 for the percentage volume of interstitial space in the various fractions of lagoon sand are comparable to those given by Bruce (1928) for similarly graded fractions of Port Erin sand. They differ, however, from Bruce's figures, both in detail and in the range of values covered by the series. Bruce found that the percentage interstitial space of sand retained by a 30-mesh sieve was only 35·8 % and that the values increased with decreasing grain size, the porosity of 30–60 sand being 39·0 %, that of 60–90 sand 42·0 % and that of < 90 sand retained by 120-mesh sieve 42·2 %. In contrast, the graded lagoon sands covered a more restricted range of porosity values from 37 to 39·5 %, and did not show the regularly ascending sequence of values with decreasing grain size observed by Bruce (see table 1). These differences between the porosities of the lagoon and Port Erin sands may be due in part to the methods of estimation used, but it is also probable

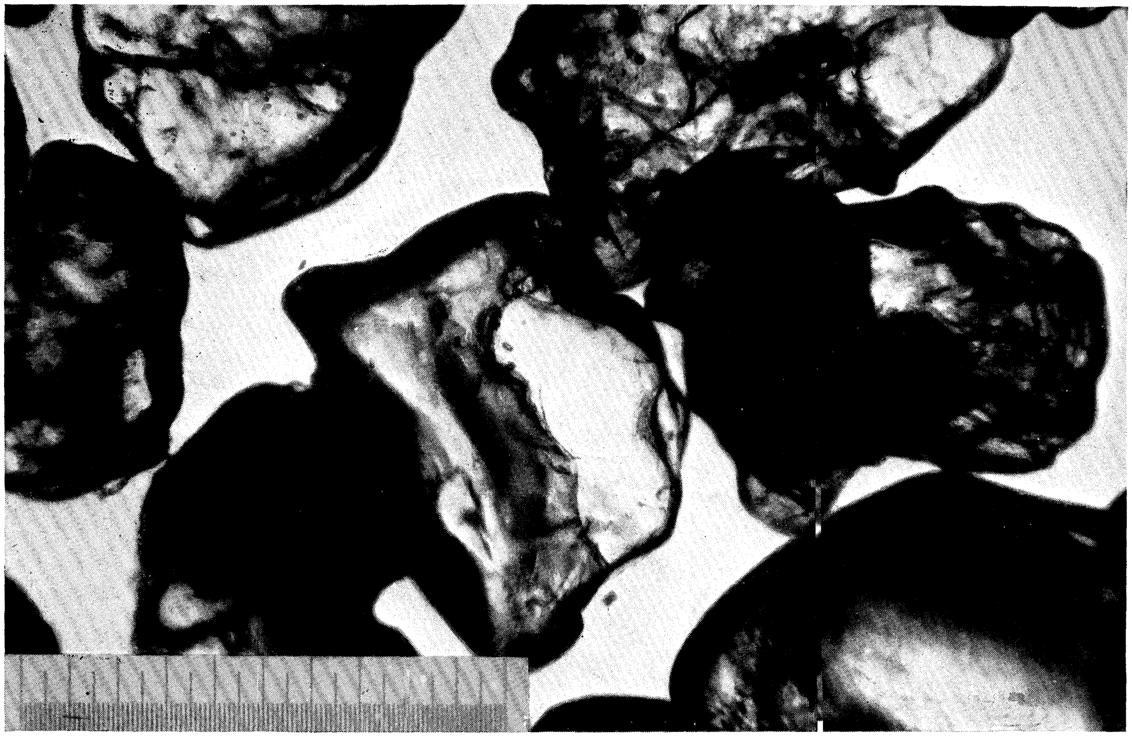

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FIGURE 10. Sand grains retained by a 30-mesh/in. sieve. Scale length 1 mm.

FIGURE 11. Sand grains passing a 30-mesh but retained by a 60-mesh/in. sieve. Scale length 1 mm.

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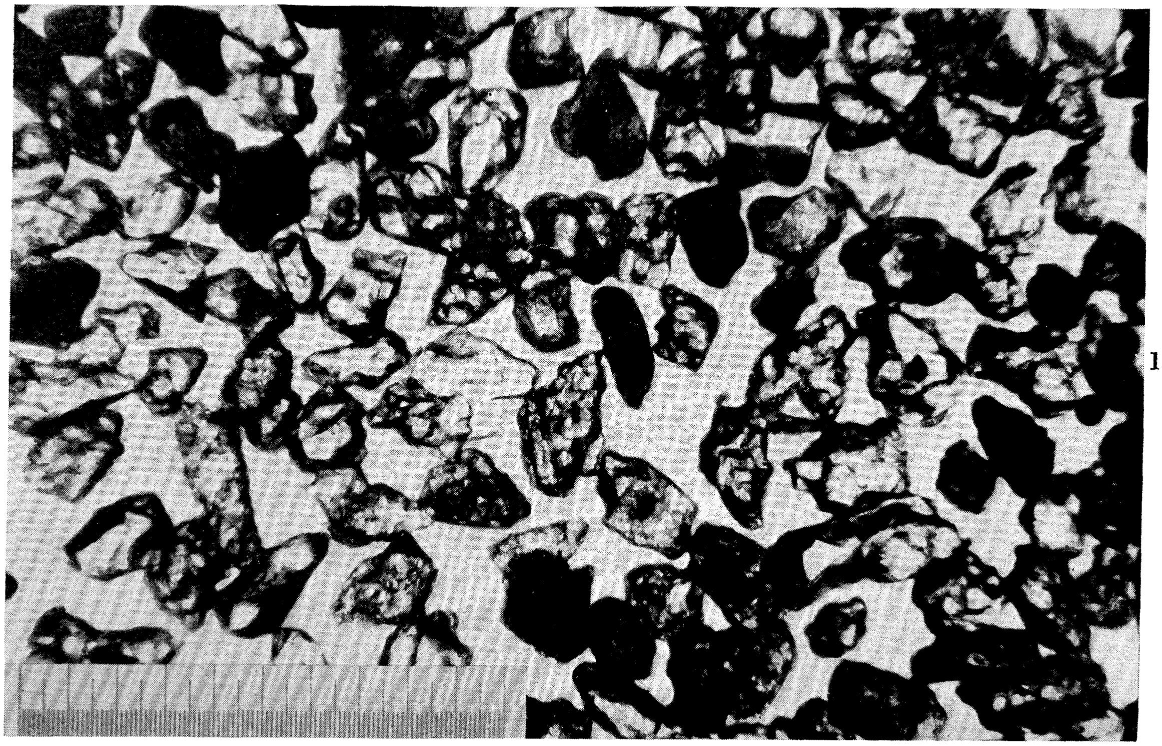

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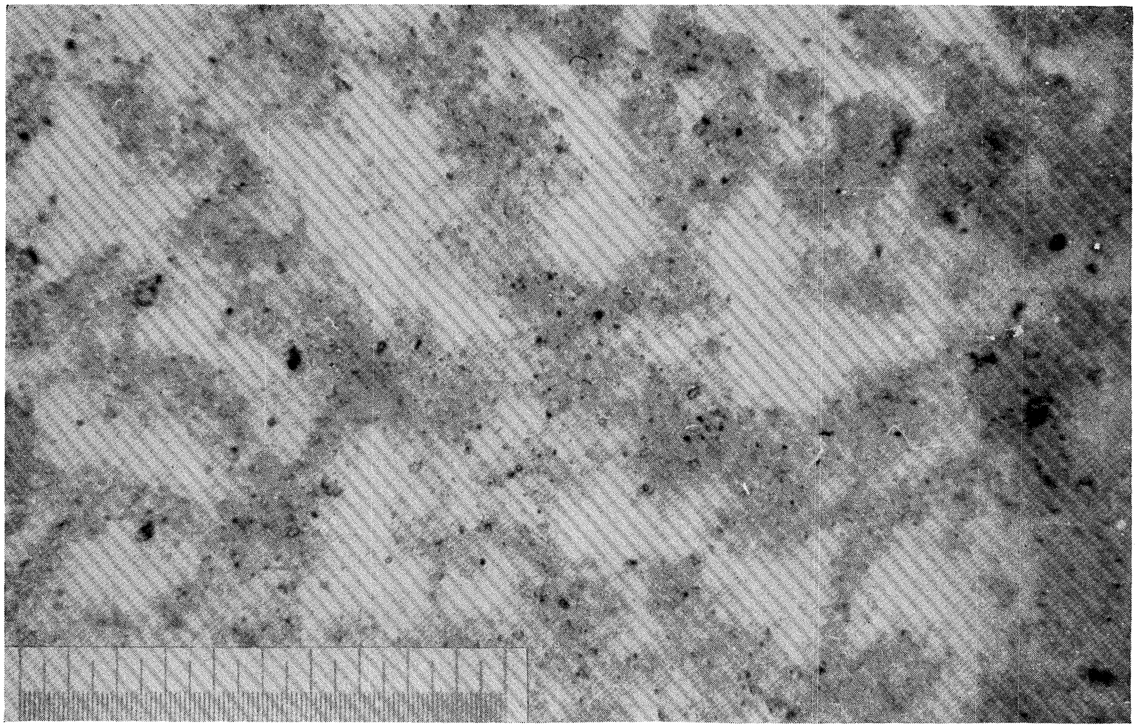
FIGURE 12. Sand grains passing a 60-mesh but retained by a 90-mesh/in. sieve. Scale length 1 mm.

FIGURE 13. Sand grains passing a 90-mesh/in. sieve. Scale length 1 mm.



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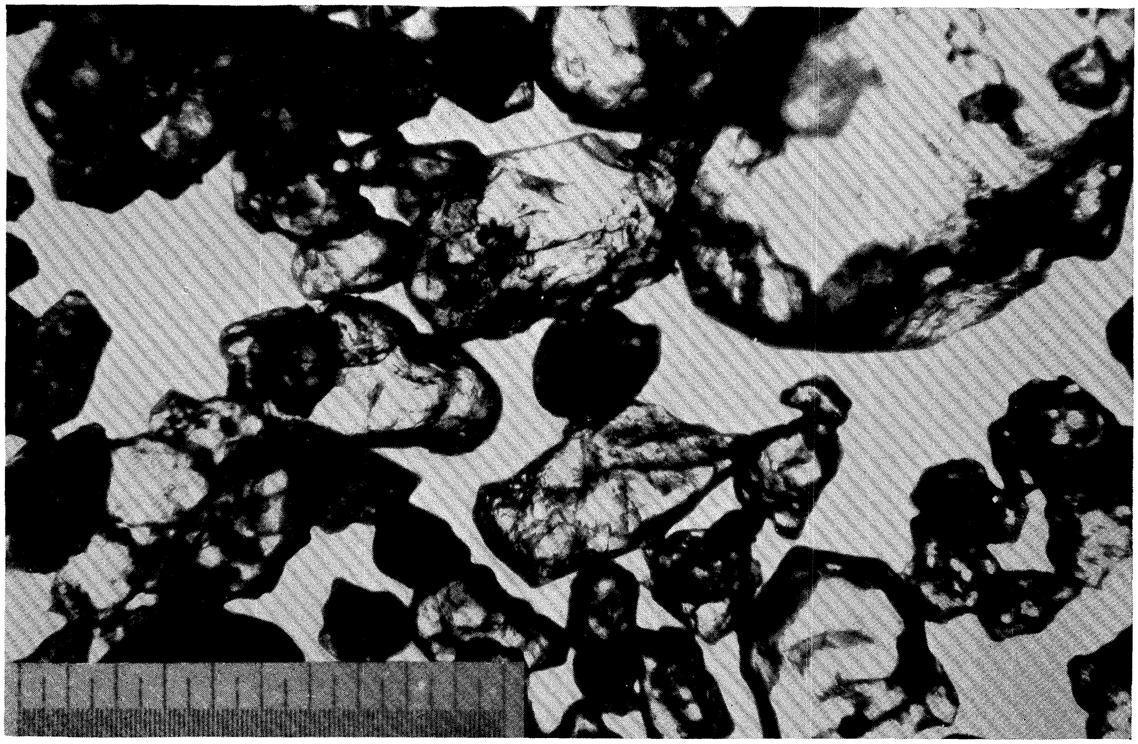

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FIGURE 14. Silt extracted from lagoon sand. Scale length 1 mm.

FIGURE 15. A natural sand from the lagoon north of Ikoyi Island, Lagos. Scale length 1 mm.

that differences in shape of the grains in the two sands may have led to variations in porosity.

The differences between the porosities of the various grades of lagoon sand were evidently real since repeated estimations carried out on the same sand showed that inaccuracies in determining the point at which the sand became saturated did not account for an error greater than ±2·0 %. In table 1 the weight of interstitial water is also compared both with the ratio between the diameter of the smallest and largest grains in each sieved fraction and with the shape of the grains. From these comparisons it appears first that the porosity of the fractions with rounded or subrounded grains was relatively higher than that of the fractions with angular grains, suggesting that porosity decreased with angularity, and, secondly (as, in the two fractions with subangular grains, the porosities were not the same) that the porosity varied with grain size. As the porosity of a sand composed of equal parts of all grades was considerably less than that of individual fractions, it may be presumed that porosity varied inversely with the relative range in grain size rather than with any absolute measurement of the size of the grains themselves. A relationship such as this would be expected if the spatial arrangements of the grains were in any way analogous to a system of spheres. The fraction with the highest porosity was the sand passing a 60-mesh but retained by a 90-mesh sieve where the diameter ratio was 1:2 and the grains were subangular. The sand retained by the 30-mesh sieve had a diameter ratio of 1:3 which should suggest a low porosity but the grains in this fraction were rounded. The sand passing the 90-mesh sieve was a more uniform fraction than the diameter ratio suggests there being fewer grains at the lower limit of the range of size than at the upper, thus, although the grains were subangular, the porosity tended to be high. It is clear, therefore, that the observed porosities of the fractions were broadly in agreement with the relative differences in range of grain size, taken in conjunction with the degree of roundness of the grains.

The porosity of simple mixtures of graded sands

To show the changes in porosity which might be expected to occur in mixed sands of different composition, measurements were made on the porosity of a number of mixtures of the four grades. These were prepared in such a way that each grade was mixed in turn with the remaining three in proportions covering a range from 10 to 90 % of the added fraction and the weight of water needed to saturate 100 g of each dry sand mixture determined. The mixtures used and their porosities thus expressed are given in figure 3.

Unlike the system of uniform spheres with smaller spheres added, when two grades of sand were mixed the porosity of the mixture was found in all cases to be lower than that of either of the constituent fractions, although the extent of the fall depended on the porportions of the grades present and the disparity in grain size. The absence of increase in porosity in any of these mixtures must have been due to the fact that the grains were not spherical and that their distribution was approximately random. Reduction in porosity when sands of different grain size were mixed thus indicates that particles of different size pack more closely than those of uniform size, the smaller particles tending to occupy the interstices between the larger. It is evident, therefore, that the most efficient packing should occur when the coarsest and finest fractions are mixed and that packing would become progressively less close as the differences in size between the grains diminished.

This is borne out by the results given in figure 3, which show that when sand retained by the 30-mesh sieve was mixed in equal proportions with sand passing the 90-mesh sieve the porosity fell to a minimum, 100 g of the mixture holding a little under 17 g of interstitial water. In 50 % mixtures of the coarse fraction with the 60–90 and the 30–60 fractions, on the other hand, values of 18·7 and 19·3 g respectively for interstitial water were obtained. Mixtures of any two of the 30–60, 60–90, and the passing 90-sieve sands in equal parts, where the differences in grain size were comparatively small, showed a reduction in porosity less than in mixtures where the sand retained by the 30-mesh sieve was used. These reductions were in accordance with the degree of difference between the mean size of the grains in the fractions mixed. Even in a mixture of the coarsest and finest sands the reduction in porosity was less than would have occurred if all the grains of fine sand had found their way between the larger grains and caused no spatial disturbance. The mean diameter of the grains of the passing 90-mesh sand was less than 0·225 that of the mean diameter of the grains of the coarse sand retained by the 30-mesh sieve and thus, had the grains been spherical, 10 % of the finer sand could have been accommodated in the interstices between the coarse grains without spatial rearrangement of the lattice. When the coarse sand had added to it 10 % of the passing 90-mesh sand, the porosity fell from 23·2 g to only 19 g of water per 100 g drys and while, theoretically, if all the fine grains had been contained in the original interstices of the coarse sand, the fall should have been to 15·3 g. Thus even with these extremes of size of grain some expansion of the lattice of coarse grains evidently took place through wedging of small grains between the large. It can be stated, therefore, that when two grades of sand are mixed, some of the small grains occupy the interstitial spaces between the large grains and reduce porosity, while others become wedged between the larger grains and,

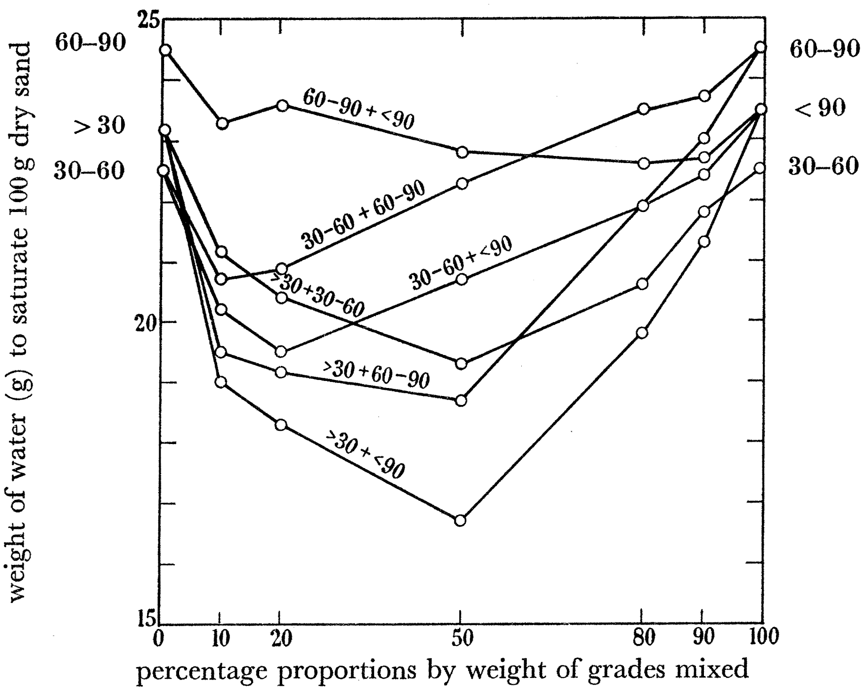

Figure 3. Graph showing the porosity of mixtures of different grades of sand.

forcing them apart, cause an expansion of the lattice, the porosity of the mixture depending on the relative sizes of the grains and the extent to which either of these processes predominates.

TABLE 2

grades of sand mixed	percentage mixture achieving minimum porosity	maximum fall in porosity (g water/100 g dry sand)	ratio between mean diams of grains in grades mixed	ratio between ranges in size of grains in grades mixed	grain shape
> 30/ < 90	50:50	6·6	9:1	14:1	rounded/ subangular
> 30/60–90	50:50	5·2	5:1	14:1	rounded/ subrounded
> 30/30–60	50:50	3·6	3:1	14:3	rounded/ subangular
30–60/ < 90	80:20	3·5	3:1	3:1	subangular/ subangular
30–60/60–90	90:10	2·8	2:1	3:1	subangular/ subrounded
60–90/ < 90	20:80	1·4	1·5:1	1:1	subrounded/ subangular

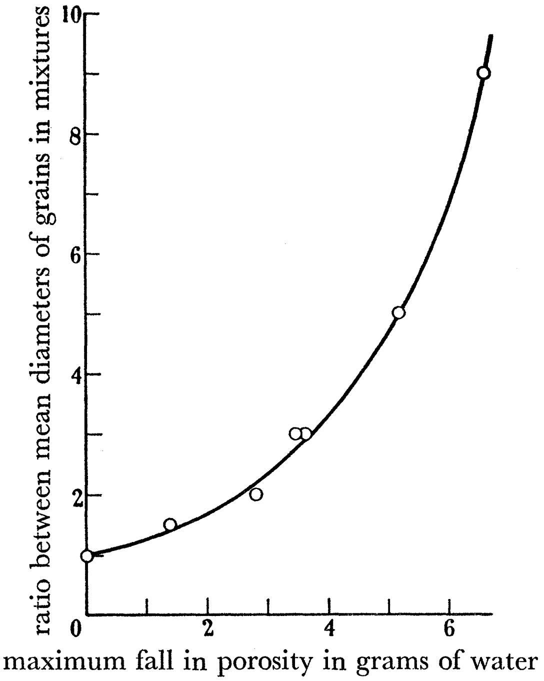

FIGURE 4. Graph showing the relationship between maximum fall in porosity occurring when different grades of sand are mixed and the ratio between the mean grain sizes of the grades.

Table 2 gives for each mixture of two grades of sand first the ratio between the mean diameter of the grains in each and, secondly, the maximum fall in porosity as shown by the difference between the minimum porosity of the mixture and the mean of the porosities of the constituents. When the ratio between the mean diameter of the grains is plotted against maximum fall in porosity in figure 4, it is seen that a curve is obtained which suggests a relationship between relative grain size and porosity and implies that the maximum reduction in porosity possible through mixing these sands of different grain size is about 30 % or a little less. It is of interest that this theoretical maximum reduction is similar to that obtaining in a hypothetical system of uniform spheres of radius a to which 10 % of spheres of radius 0·225a have been added. The curve in figure 4 is approximately a parabola, showing that there is a linear law between y and x^2, where y is the ratio of the mean diameters of the grains in the mixture and x is the maximum fall in porosity.

The curves showing the porosity of the mixtures in figure 3 are of two kinds. In mixtures with the sand retained by the 30-mesh sieve, the curves have the point of least porosity at or near the 50:50 mixture. In the remaining three series the point of least porosity occurs when the proportions of the two constituents are unequal, that is when a small quantity of one sand, usually the finer, has been added to the other. The difference in the form of the curves is evidently not due to difference in the ratio between the mean diameters of the grains in the grades mixed for, in the case of the >30/30–60 and the 30–60/<90 mixtures, the ratio and the minimum porosity are very nearly the same, but the proportions of the mixtures at which minimum porosity occurs are different, the curve in the first case being more or less symmetrical and in the second grossly asymmetrical (see figures 3 and 4 and table 2).

Table 2 also gives the ratio between the range in size of the grains in the fraction mixed and their grain shape, and these are compared with the percentage mixtures giving minimum porosity. The ratio between the ranges in size of grains in the grades mixed indicates the relative uniformity of the grades. Thus, where this ratio is high, a comparatively uniform grade is mixed with one of considerable diversity in grain size, but where the ratio is low both grades are more or less uniform. Since the grades do not overlap and a difference in mean size of grains is implicit in the mixtures, the mixing of uniform grades with low grain-range ratio provides a system more nearly akin to the system of large spheres intermixed with small than the mixtures with a high grain-range ratio. It is seen that in all cases where minimum porosity occurs at about the 50:50 mixtures, a grade of sand with comparatively uniform grains is added to one in which the range of grain size is much greater. On the other hand, the mixtures of 30–60 sand with 60–90 and <90 sand respectively, where the range of grain size in the fractions is not greatly different, being in ratio 3:1, minimum porosity occurs when 10 % and 20 % in each case of the finer sand is added to the coarser. In the 60–90/<90 mixture the range of grain size is equivalent in the two fractions and here an approach to minimum porosity is obtained at two points when 10 % of either fraction is added to the other.

In all mixtures some of the grains in the finer sand are between 0·414 and 0·225 times the diameter of some of the larger grains in the coarse sand (see table 1) and thus, were the grains spherical, could be accommodated in the interstices of the lattice without undue expansion of the interstitial spaces. The fact that minimum porosity in mixtures with low grain-range ratio is achieved when 10 to 20 % of the finer grade is added to the coarser suggests strongly that the spatial arrangement of the grains in these mixtures is similar to that obtaining in the hypothetical mixture of the different sizes of spheres.

The difference in the porosity curves of mixtures with low and high grain-range ratio probably arises from the nature of the interstitial spaces in the lattice formed by the dominant grade. The pore spaces in a graded sand are as diverse as the size of the grains. In a mixture of low grain-range ratio where fine grains are added to a comparatively uniform sand with equally uniform interstices, the finer particles evidently tend first to fill the pores in the lattice with little displacement of the larger grains. After 10 to 20 % of fine sand has been added, the full capacity of the lattice to absorb fine grains without undue spatial disturbance appears to be reached and further additions cause a general disruption with expansion of the interstitial spaces in excess of the volume of the added fraction. Thus minimum porosity occurs immediately before the point of general disruption of the lattice and varies according to the size of the grains added.

In a mixture of high grain-range ratio fine grains are added to a sand in which, owing to diversity in size, the spatial arrangement of the grains is highly irregular and the interstitial spaces correspondingly varied in volume. The fine grains, therefore, tend both to fill the larger spaces and to disrupt the finer interstices which they are too large to occupy without expansion. Thus, although the occupation of the larger spaces predominates at first, there is an appreciable expansion of the smaller spaces at the same time and a continual rearrangement of the grains forming the lattice. At no point, therefore, is there a sudden and general disruption of the lattice as postulated in mixtures of low grain-range ratio. It has already been shown that porosity varies inversely with the relative range in grain size. As the coarser grade in a mixture of high grain-range ratio is by nature itself a mixture of different sizes of grain and not a uniform sand, the addition of finer grains only serves to increase the range of size, giving maximum diversity throughout the mixture and hence minimum porosity when two grades are present in approximately equal proportions.

Where coarse grains are added to a fine sand, on the other hand, the spatial arrangement of the grains is different. The coarse grains lie in a bed of fine grains and are not necessarily in contact with one another. The addition of coarse grains to a fine sand, therefore, reduces porosity by displacement. This is shown, for example, in figure 3 where 10 % of grains retained by the 30-mesh sieve added to sand passing the 90-mesh sieve reduced porosity by 10 %. The comparable addition of 10 % of the fine sand to the coarse reduced porosity by 18 % and theoretically, if all the fine grains had been accommodated in the original interstices of the coarse sand, would have reduced porosity by 34 %. The porosity curves in figure 3 show in every case that porosity falls more steeply when the finer sand is added to the coarser than when coarse grains are added to the fine.

The shape of the grains has been shown to affect the porosities of the graded sands themselves and clearly must also affect the general levels of porosity in the mixtures. There is no evidence, however, that the form of the porosity curves for the mixtures in figure 3 and their position relative one to another was greatly affected by differences in grain shape.

The porosity of natural sands

From these measurements of porosity in simple mixtures of two grades of sand it is evident that, in lagoon sands of mixed character, porosity should be related to the grain size of the dominant fractions present and the proportions of other fractions mixed with them. To show the degree of difference in porosity in natural sands, five sands of different types were selected from deposits in Lagos harbour and lagoon (see part II), analyzed by sieving to determine the proportions of each grain size present, and the weight of water saturating 100 g of each sand measured. The composition of the sands chosen is given in table 3, together with the estimated value for porosity.

It was found that there was a general increase in porosity with decrease in grain size of the dominant fraction, the coarser sands holding less water than the fine sands. These sands were of two types, first those in which reasonable proportions of all grades were present and the dominant fraction occupied only about 50 % of the whole, and, secondly, those in which the dominant fraction comprised about 70 to 80 % of the entire sample. In the first group were the sands of Onikan and the lagoon north of Ikoyi Island, and in the second the harbour sands and the sand of Lighthouse Creek (see part IV, figure 6). The small quantity of silt present did not seem greatly to affect the porosity of the sand and was ignored. The sands of the West Harbour and Lighthouse Creek from which the samples were taken were both unstable sands, the former to such an extent as to form a quick sand, while those of the East Harbour, Onikan and the lagoon north of Ikoyi Island, which were more mixed in character or had a high proportion of large particles, were stable. Burrowing animals of small to moderate size were notably absent in the unstable sands but were present in stable sands as shown by the incidence of lancelets indicated in table 3.

TABLE 3

	sieved fractions (%)					water to saturate 100 g dry sand (g)		incidence of lancelets
locality of sand	> 30-mesh	30–60-mesh	60–90-mesh	< 90-mesh	silt		stability of sand	
Onikan	28·75	46·00	12·75	11·00	1·50	18·5	stable	common
East Harbour	8·40	77·75	13·00	0·75	< 0·10	19·5	stable	common
Lagoon north of Ikoyi Island	3·0	32·0	54·4	9·5	1·1	21·5	stable	very common
West Harbour	< 0·10	6·5	77·8	15·5	< 0·1	22·0	very unstable (quick sand)	rare
Lighthouse Creek	2·3	8·4	15·8	68·0	5·5	23·0	unstable	absent

The stability of a natural sand appears to be connected with porosity and grain size. The unstable sands of the West Harbour and Lighthouse Creek both had a high porosity and a high proportion (over 90 %) of grains passing a 60-mesh to the inch sieve, and presumably owed their lack of stability to the fact that the uniform particles tended to move easily one against the other in the abundant water present. However, instability was not due to either high porosity or small particle size alone, for the stable North Ikoyi Island sand had a porosity nearly as high as the West Harbour sand which in turn was even less stable than the Lighthouse Creek sand with both a higher porosity and a finer texture (see table 3). A third factor, therefore, must be operating to produce the quick sands of the West Harbour. A sand of grains of mixed size, on the other hand, with a low porosity forms a hard stable sand capable of resisting considerable pressure even when completely submerged. In this case the sand grains of different sizes evidently tend to interlock, the small wedged between the large, and the sand holds insufficient water to permit free movement of the grains.

The presence of lancelets in the stable sands of North Ikoyi Island, East Harbour and Onikan, and their absence from the unstable sands of the West Harbour and Lighthouse Creek, suggests that the volume of water in the sand is not itself a limiting factor in their distribution so far as the sands tested are concerned, although its influence on stability when taken in conjunction with the composition of the sand may give rise to conditions under which burrowing animals cannot live. An unstable sand may provide neither adequate protection for burrowing animals nor a medium through which rapid movement is possible.

Capillary lift and capillary water

In intertidal sands at low tide burrowing animals are dependent on the water held in the interstices by capillarity against seepage for the maintenance of aquatic conditions. Clearly the volume of the interstitial water available to animals living in these sands during periods of exposure will be governed first by porosity of the sand and, secondly, by the size of the pores in so far as this affects the rise of capillary water above the water-table. The capillary rise in various graded sands was measured by the following method. The base of a column of dry sand in a length of glass tubing covered at the bottom by a piece of cotton lawn secured with a rubber band was placed in water. When the movement of water up a column of sand by capillarity had ceased, the height of the capillary rise was measured, the dry sand remaining above the wet was poured off and the wet sand removed and weighed. This sand was then dried and reweighed to give by subtraction the weight of water absorbed by the sand. The amount of capillary water absorbed was then expressed as the weight of water held by 100 g of sand. Measurements of capillary rise and capillary water were made on each of the four graded sands separated by 30-, 60- and 90-mesh to the inch sieves. The results obtained are given in table 4. As the total volume of water raised by capillarity is a function of both the height of the capillary rise and the weight of capillary water held by a given weight of sand, a measure of this total water held against gravity was obtained from the product of these two variables. When the product of the capillary rise and the weight of capillary water per 100 g dry sand is plotted against the average diameter of the grains in each fraction as in figure 5, a curve is obtained showing that the total volume of water held by capillarity in a sand is a function of the grain size. This curve is a rectangular hyperbola with asymptotes parallel to the co-ordinate axes. A graph in which the average diameter of the grains is plotted against the reciprocal of the product of the capillary rise and the weight of capillary water held by 100 g sand shows a linear law with the line cutting the ordinate axis at approximately 0·025 which is at or near the lower level of size for quartz grains.

TABLE 4

grade of sand (mesh/in.)	average diameter of grains (mm)	height of capillary rise (cm)	capillary water absorbed (g/100 g dry sand)	capillary rise × capillary water
> 30	0·9	4·7	22·1	104
30–60	0·45	9·7	22·6	219
60–90	0·25	15·37	26·4	406
< 90	0·15	33·5	23·5	787
above grades mixed in equal parts	0·395	13·3	17·9	248

As would be expected the capillary rise in the different grades of sand increased with diminishing pore size as determined by the size of the sand grains present. The weight of capillary water absorbed by 100 g of dry sand, on the other hand, neither varied regularly with grain size nor agreed with the porosities of the sands given in table 1 and measured as the water to saturate 100 g dry sand. Whereas the water absorbed by capillarity and the water required to saturate were approximately equivalent in the 30–60- and the passing 90-mesh sands, in the sand retained by a 30-mesh sieve capillary water was less than that needed to saturate, while in the 60–90 sand it was appreciably greater. Thus it may be assumed that water drawn into the coarse sand by capillarity left a proportion of the interstitial spaces unfilled, in the 30–60- and passing 90-mesh grades all available interstitial space was filled, but in the 60–90 sand capillarity was sufficient not only to fill all available space, but also to force the grains apart, expand the lattice, and thus increase porosity.

It was noticed that the quicksand from the west side of Lagos harbour contained a high proportion of grains of 60–90-mesh grade. It was thought that the reason for the lack of stability in such sand might be due to displacement of grains through the action of capillary forces. An area of beach was selected in which quicksand was flanked on either side by firm sands. Samples were taken of the quicksand and the firm sands immediately to the north and south. The samples were analyzed, their porosites determined as the weight of water required to saturate 100 g dry sand, and the capillary rise and also the weight of capillary water held by 100 g of each was measured. The results are given in table 5. There was comparatively little difference in the composition of the three sands except that the quicksand contained a higher proportion of the 60–90 and 30–60 grades and less passing 90-mesh sand and in consequence had a lower porosity and a lower capillary rise. Thus the instability of the quicksand could not have been due to either high porosity or high capillary lift alone.

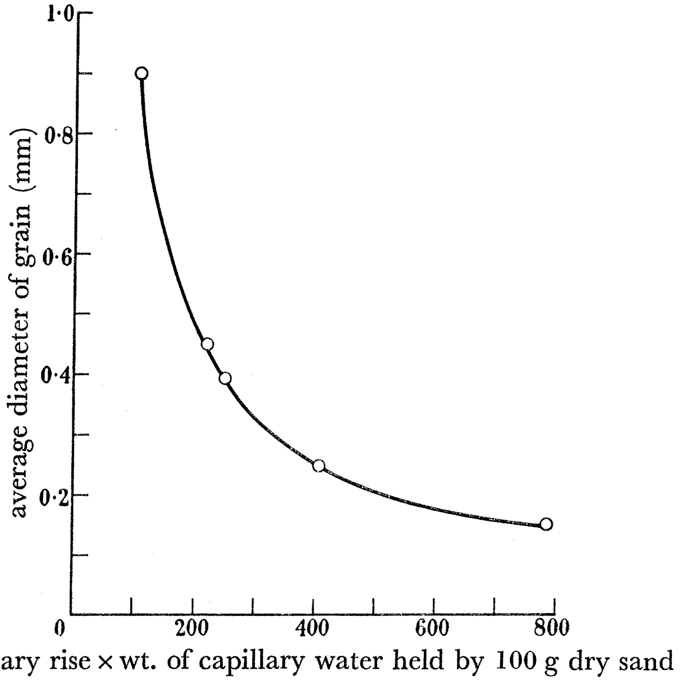

FIGURE 5. Graph showing the relationship between the volume of water held by different sands and the size of the grains.

However, when the water required to saturate the sand was compared with the weight of capillary water, it was noticed that, whereas in the firm sands the capillary water was less than that needed to saturate, in the quicksand the reverse was the case. This then would appear to be the cause of the instability of the quicksand. The sand evidently becomes supersaturated with capillary water. Such an expansion of the lattice by capillary forces must result in a reduction of the number of contact points between the grains and an increase in the number of floating grains (see Gaither 1953). That this phenomenon seems to occur principally in the 60–90-mesh sand and not in sands of either finer or coarser texture is evidently connected with both grain size and grain shape. It has already been mentioned that the 60–90 grade of sand is exceptional in so far as the grains are more uniform than in any other grade, as shown by the ratio between the diameters of the smallest and largest grains. They also approach sphericity as they are subrounded in shape (see table 1 and figure 12, plate 16). It is evident that here is a case where the force of capillarity is greater than the resistance of the sand grains to movement. In both coarser and finer sands which are not quicksands the capillary force is clearly not sufficient to overcome the resistance of the grains. In the coarse sand this could be due to low capillarity in the relatively large pore spaces in conjunction with the greater weight of the large grains. In the finer sand passing a 90-mesh sieve stability must be due to the high resistance of the subangular grains to movement since the capillary forces are considerably greater in this fraction than in the 60–90 fraction.

Table 5

	sieved fractions (%)							
location and stability of sand	fine shell > 30-mesh	30–60-mesh	60–90-mesh	< 90-mesh	water to saturate 100 g dry sand (g)	height of capillary rise (cm)	capillary water absorbed (g/100 g dry sand)	difference between capillary water and water to saturate
North, firm	—	3·5	43·5	53	26·1	27·7	25·6	−0·5
Quick	0·2	18·6	54·2	27	25·5	23·5	26·4	+0·9
South, firm	0·3	13·9	46·8	39	27·3	26·5	25·1	−2·2

As seen from tables 1 and 5, the porosities of these three sands are very high compared with that of the 60–90 grade of sand alone or the West Harbour sand analyzed in table 3. The reason for this is not clear unless it is assumed that in these mixtures an expansion of the 60–90 lattice is caused by the presence of particular quantities of 30–60- and < 90-mesh grains similar to that occurring in uniform systems of spheres on addition of small quantities of other spheres too large to fit into the interstices.

The permeability of sands

Although the volume of water contained in the interstices of an intertidal or permanently submerged sand affects the physical characteristics of the deposit, and thus may be a factor determining the distribution of burrowing animals, the freedom with which the water can circulate between the grains should be even more important at least to animals that do not live in tubes. An animal living in sand without a tube leading to the surface through which a water current can be maintained must be dependent on the circulation of water in the sand itself for supplies of oxygen and for the removal of waste products. Thus factors governing permeability are likely to influence the selection of a deposit by sand-dwelling animals. The permeability of a sand is dependent upon pore size and not porosity. It has been shown that fine sands in general hold rather more water than coarse sands, but, by virtue of the small size of the pores, they are far less permeable. The extent to which the contained water in a sand is free to circulate between the grains may depend first on the degree of retention of water in the finer interstices by surface forces, and, secondly, on the diameter of the larger channels through which water can flow.

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The retention of water by surface forces

In a sand draining under gravity, a film of water coating the grains is held by surface forces and in submerged sands again a significant proportion of the volume of water in the sand may be similarly held so tightly in the finer spaces between the grains as to be unavailable for circulation. In order to obtain an estimate of the proportion of the contained water available for free circulation, the rate of evaporation from different sands was measured under uniform conditions and the point at which a change in rate occurred due to retention of the water by surface forces was noted.

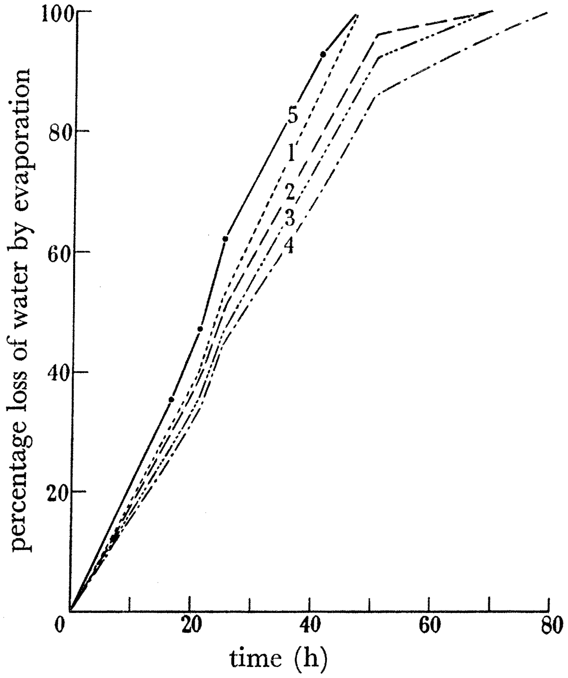

FIGURE 6. Graph showing the percentage loss of weight by evaporation from sands of different grain size saturated with water. ----- 1: sand retained by 30-mesh/in. sieve. ——— 2: sand passing 30-mesh but retained by 60-mesh/in. sieve. —··· 3: sand passing 60-mesh but retained by 90-mesh/in. sieve. —·— 4: sand passing 90-mesh/in. sieve. ——— 5: sand composed of equal parts of grades 1–4.

Equal quantities by weight (40 g) of each of the four grades of sand obtained by sieving through 30-, 60- and 90-mesh sieves were placed in small Petri dishes (4 cm in diameter) of similar surface area. In a fifth dish a mixture of equal parts by weight of each grade was prepared. The sand in each dish was first agitated by tapping to settle the grains into a compact mass, then saturated with water and the weight of the water calculated. The dishes were placed in a position free from draughts and weighed at intervals to determine the loss of weight by evaporation until the sand was dry. In view of the differences in porosity of the sands, a direct comparison of the rate of evaporation could only be made over the first 40 h of the test by which time none of the sands was dry. The percentage loss of water from each sand, therefore, was plotted against time (figure 6).

The rate of evaporation from sand retained by a 30-mesh to the inch sieve approximated to that from a free water surface and was more or less constant until the sand was completely dry (see figure 6). The rates of evaporation from the finer grades, however, were less than that from the coarse sand, and varied according to the size of the grains. As dryness was approached in these sands, evaporation suffered a check so that the last of the water was lost at a much slower rate. In the mixture of equal parts of the four sand fractions, the absolute rate of evaporation was slower than in any of the constituent fractions, but, as the porosity, and therefore the water content, of the mixture was also much lower, evaporation to dryness took place as rapidly as in the coarse sand (figure 6). There was, however, a slight reduction in the rate of evaporation from the mixture as dryness was approached.

The change in the rate of evaporation in the finer sands as dryness was approached is held to be due to the effects of surface forces in tending to maintain small columns of water between the grains against evaporation.The point at which the change in rate occurred gives a measure of the amount of water so held. In the sand retained by the 30-mesh sieve the water held against evaporation was negligible. In the remaining fractions the amount held increased with decreasing particle size, the 30–60 grade holding 4·5 % of interstitial water, the 60–90 grade 8 % and the <90 grade about 14 %. The mixture held 7·5 % of its interstitial water against evaporation, a figure which is intermediate between those of the grades. Thus the amounts of water in any of these sands likely to be affected by surface forces and therefore unable to contribute to a free circulation between the grains were comparatively small. In similar experiments on the evaporation of water from sand, Bruce (1928) also found that the rate approximated to that from a free water surface, but stated that there was little difference in the rates of evaporation from different grades of sand. In the present experiment this was certainly the case for the first 24 h of the test, but thereafter appreciable differences in rates of evaporation arose according to the grade of sand, evaporation from the deeper layers being more rapid in coarse than in fine sands. These differences in the rates of evaporation prior to the check imposed by surface forces were evidently due to the size of the pores in the dry sand above the evaporating surface. Differences in pore size which could influence the diffusion of water vapour away from the evaporating surface would also determine the rate of flow of water currents through the sand.

The drainage of water through sands

The extent to which pore size interferes with the free circulation of water in a sand deposit can only be measured directly. Although it has been shown that, even in the finest sands, the greater part of the contained water is free to circulate, the movement of that free water will depend on the existence of forces such as those set up by the activities of buried animals in maintaining respiratory and feeding currents, on convection due to differences in density of the water or, in intertidal sands, on gravitational pull where fluctuations in the level of the water-table occur. Thus the rate of drainage of water through a sand gives a measure of the ease with which water movements initiated by any of these means may take place and should apply both to intertidal and to permanently submerged sands.

The following method was used to determine the permeability of different sands according to the rate at which water flowed between the grains. A glass tube 1·5 cm external diameter and 70 to 80 cm long was fitted with a centimetre scale cut from graph paper and covered by a strip of transparent plastic adhesive tape. A piece of cotton lawn was stretched over the bottom of the tube and secured by a rubber band, while the top of the tube was sealed when necessary by a small rubber bung. The tube was held vertically in a clamp above a conical flask containing distilled water. The rate of flow of water through a stable 10 cm column of sand was measured by the time taken for a head of 65 cm of water to drain to the 15 cm mark on the scale. The sand in the tube was considered stable when the drainage times in three consecutive trials did not differ by more than ±0·5 %. In order to achieve this degree of accuracy it was found that the sand must be uniformly mixed, free from air, fully settled (i.e. the level of the column does not fall when the tube is tapped) and the grains at the surface must not form an adherent compacted mass. Several methods were used to prepare columns of sand in conformity with these standards, but only the most satisfactory is described.

The sand sample to be tested was dried in air and a small quantity of the loose sand poured into the dry graduated tube, the cloth-covered end being held just beneath the surface of the distilled water in the conical flask. Time was allowed for the water to seep into the sand until the surface of the sand was wet. The tube was then lowered into the water until the external water level reached that of the surface of the sand, when more dry sand was added. This procedure was repeated until a column about 1 cm higher than that required was obtained. The clamp holding the tube was released and the tube lowered into the water and gently tapped on the bottom of the flask until the level of the sand remained constant. The final height of the column was then adjusted if necessary by the addition of more sand. It was found to be important at this stage not to remove the tube from the water in the flask. The tube was then filled to the brim with distilled water and corked, removed from the flask and rotated slowly in the hands, gradually tipping until the cloth-sealed end was at a higher level than the corked end. These movements distributed the sand along part of the length of the tube, releasing air bubbles and ensuring an evenly mixed sample. The tube was then returned slowly to the upright position with continued rotation. The column thus re-formed was again settled by tapping either on a soft pad on the bench or under water, when coarse sands were tested. The tube was then clamped above the flask, uncorked, and the water allowed to drain through the sand until the water level reached the 15 cm mark. The tube was refilled with distilled water, the process repeated three or four times and then, with water standing above the sand in the tube, the end was lowered beneath the water in the flask, the bung re-inserted and the column allowed to stand in this position overnight. This period was essential to allow time for the dried silt with organic matter in the sand to take up water and thus restore the sand sample to a condition approaching that in which it was first collected. The next day and thereafter water was repeatedly drained through the sand until three consecutive readings tallied. Between tests, when necessary, the tube was filled with water, corked, and rotated in the horizontal position to disturb and mix the upper 0·5 to 1·0 cm of sand only as the slow drainage of water through this layer tended to render the surface of the sand relatively impermeable and thus seriously affected the results. As it frequently required many tests before stability of the sand column was reached, it was usually necessary to leave the experiment overnight and also at other times. This could be done provided that the upper end of the tube was corked to hold a column of water above the sand and the lower end of the tube was beneath the water in the flask. On no occasion was the water level allowed to fall below the surface of the sand column. Distilled water was always used both in the flask and for drainage through the column as the dissolved air in tap water gave rise to bubbles in the sand which increased the drainage time.

Using this method, tests were made on columns of similar sand but of different heights when it was found that the relation between time of drainage and height of column is linear so that any discrepancy in the height of the column of settled sand could be corrected. Moreover, where the rate of flow of water through fine deposits was estimated, a 5 cm column could be used, with a saving in time both in stabilizing the column and in carrying out the tests. The results thus obtained could then be expressed on the basis of a standard 10 cm column.

As an indication of the permeability of sands of different grain size, the rate of flow of water through the four grades of sieved sand was measured. It was found that, whereas the drainage times for the >30-, 30–60- and 60–90-mesh fractions were 2 min 50 s, 3 min 36 s and 10 min 36 s respectively, that for the grains passing the 90-mesh sieve was 25 h 30 min. Thus, while the circulation of water in the coarser fractions was relatively unimpeded by the size of the interstices between the grains, in the fine fraction the rate of flow was nearly 150 times slower than in the adjacent 60–90-mesh fraction.

In a mixed sand the interstices between the larger grains tend to be filled with the smaller grains, so that the rate of flow of water through such a sand will depend largely on the quantity of the finest fraction present. Thus, if the freedom with which water circulates between the grains in a sand is important to burrowing animals, the proportion of fine grains to coarse may prove a limiting factor in determining the suitability of a sand as a medium for animals of this type. It was therefore considered desirable to show how increasing proportions of grains passing a 90-mesh sieve affected the rate of flow of water through a natural mixed sand in which burrowing animals other than tube-forming types were known to occur. The sand chosen for these tests was the lagoon sand from north of Ikoyi Island. The composition of this sand is given in table 3. This sand was a well-mixed medium-grade sand with a relatively high porosity. Approximately 10 % of grains passing a 90-mesh sieve and about 1·0 % of silt were present. As the tests were designed to show the effects of the fine grains in the sand, the silt fraction was removed on the grounds that the small particles of this fraction should play an independent role in determining the rate of water flow. Samples of the North Ikoyi sand, therefore, were prepared containing 0, 10, 20, 25, 30 and 40 % respectively of grains passing the 90-mesh sieve, and their permeability determined. The result of these tests is given in figure 7.

As was expected, an increase in the passing 90-mesh sieve fraction of the North Ikoyi sand decreased the rate of drainage of water through the sand. The rate of decrease, however, did not bear a linear relationship to the increase in proportion of fine sand. The addition of fine sand in amounts up to 20 % of the total by weight caused a comparatively slight lengthening of the drainage time, but, as seen in figure 7, where drainage time is plotted against the percentage of fine sand added, thereafter the curve rose more and more steeply until, at 40 % of fine sand, the time was more than doubled. This curve is approximately parabolic, indicating that the increase in drainage time is approximately proportional to the square of the percentage of sand passing a 90-mesh sieve present. Thus $y-8{\cdot}5 \propto x^2$, where $y-8{\cdot}5$ is the increase in time and x is the percentage of fine sand, there being a linear law between y and x^2. It is clear, therefore, that, in a sand of the North Ikoyi type, the presence of 10 or even 20 % of grains of the finer fraction does not greatly affect the circulation of water, but that, where this percentage exceeds 25 %, a material fall in permeability occurs. However, the drainage time of the mixture, even with 40 % of fine sand present, did not approach that of the fine sand fraction alone, so that such a mixture can be envisaged as a lattice formed by the larger grains with the spaces between tending not only to be filled by small grains but also enlarged as some of these grains wedge the large grains apart. This concept has been supported by measurements of porosity. The addition of fine sand to the North Ikoyi sand in amounts up to 40 % produced a negligible fall in porosity not greater than 4 %. Thus, although little change in the porosity of Ikoyi sand followed the additions of fine sand, there was a profound alteration in permeability. If circulation of water through sand is important to animals living in it, then it would be expected that the critical proportion of fine grains in the sand should be about 25 %, quantities in excess of this reducing the permeability of the sand to such an extent that the circulation of the water is seriously impeded. It is significant that, as shown in part IV, lancelets avoided the North Ikoyi sand containing 30 % of grains passing a 90-mesh sieve, but entered the sand readily and remained there when 10 or 20 % of the fine sand was present, the critical concentration of this grade of sand for lancelets being about 25 %. It is evident, therefore, that in these experiments the lancelets were reacting to the permeability of the sand.

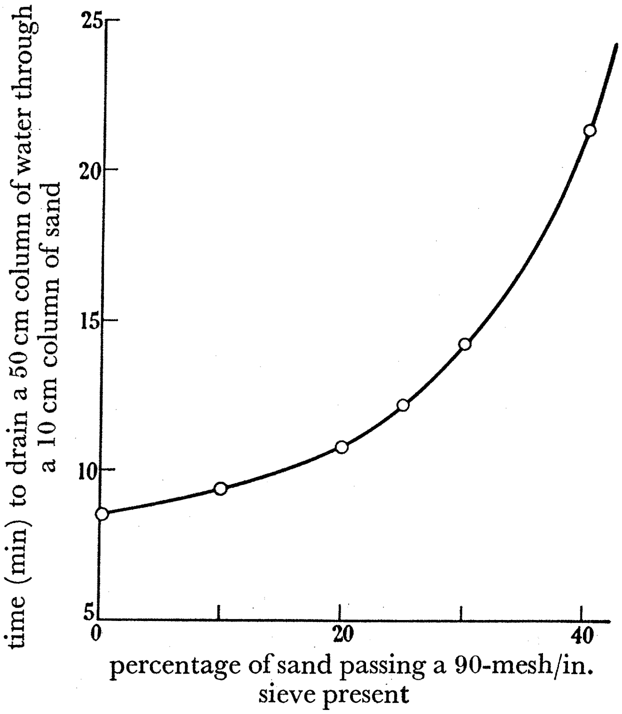

FIGURE 7. Graph showing the relation between the percentage of grains passing a 90-mesh/in. sieve present and permeability to water of North Ikoyi sand.

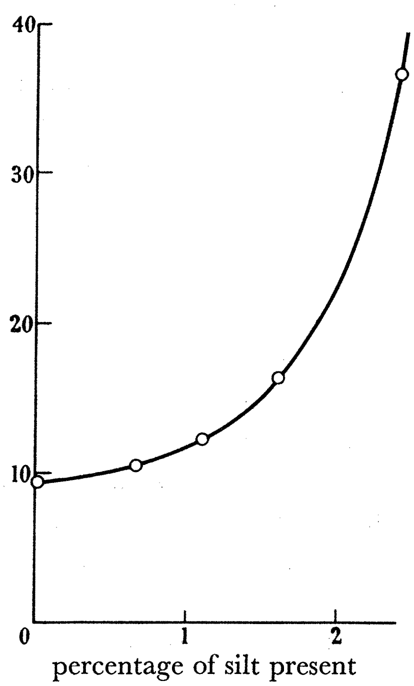

FIGURE 8. Graph showing the relation between the percentage of silt present and permeability to water of North Ikoyi sand.

Just as the proportion of fine grains in a sand determines its permeability, so a similar effect would be expected with regard to the silt fraction. The silt recovered from the lagoon sands contained a high proportion of organic matter of the order of 20 % which was largely in a colloidal state. The flocculent masses of silt, as shown in figure 14, plate 17, were therefore capable of either filling small interstices or sealing the major cavities between the larger grains and could be far more important in determining the permeability of a sand than any other single fraction. To show the effect of silt content on the permeability of sand, samples of the North Ikoyi lagoon sand were prepared first without silt and then with an increasing silt content up to nearly 2·5 % dry weight, and the rate of drainage of water through these sands determined. As the quantity of silt involved was so small the silt content of each column of sand was checked by analysis after the drainage times had been taken. The results obtained with these sands are given in figure 8.

As in the case of the addition of fine sand, the rate of increase of the time of drainage did not bear a linear relationship to the increase in silt content. The addition of silt up to about 1·0 % produced relatively small increases in time of drainage, but beyond this figure the time greatly increased until, with 2·4 % silt, the drainage time was nearly four times that for the silt-free sand. As seen from the graph in figure 8, therefore, the point of inflexion of the curve for drainage time against silt content lies at about the 1·4 % level when drainage takes a little over 14 min. This curve, like that in figure 7 for the addition of passing 90-mesh sand, is also approximately parabolic. Thus $y-9{\cdot}4 \propto x^2$, where $y-9{\cdot}4$ is the increase in drainage time and x the percentage of silt present in the sand, there being a linear law between y and x^2.

In comparing the relative effects of fine sand and silt in restricting water movement in the North Ikoyi sand it should be remembered that, in the silt tests, the natural sand used contained about 10 % of grains passing the 90-mesh sieve. Thus in figure 8 the reading for sand free from silt is comparable to that for sand with 10 % of fine grains in figure 7 and not to the reading for sand free from fine grains. For a direct comparison, therefore, of the effects of fine sand and silt it is necessary to reduce the times for silt by a little under 1 min since it is evident that the effects of fine sand and silt will be additive. When this correction has been made it is found that the curves for fine sand and silt are almost exactly the same except that, at the lower readings, the curve for silt is slightly flatter than that for fine sand and at the higher readings rises rather more steeply.

It has already been shown that the concentration of fine sand at which the permeability of the mixture begins to fall off sharply is between 25 and 30 %. From figure 8, it can be seen that a similar condition obtains with the silt fraction, but in this case when the concentration is only 1·4 % or a little less. In both cases at these critical concentrations the rate of drainage in the North Ikoyi sand is approximately the same, the time taken to drain a 50 cm column of water through 10 cm of sand being 12 to 13 min. It is evident, therefore, that 25 % of fine sand grains and 1·4 % of silt restrict the flow of water to the same extent. Again it was shown in part IV that lancelets would not tolerate sand deposits in which the silt content was above 1·5 %, indicating that there was a limiting permeability of the deposit to which the animal reacted and that this was reached when either 25 % of passing 90-mesh grains or 1·5 % of silt were present.

It would appear, therefore, that the fine sand ($<0{\cdot}2$ mm in diameter) and the silt fractions are the most important in determining the permeability of a sand. The results given, however, apply only with regard to the addition of fine sand and silt to a specific mixture of larger particles, that is to the lagoon sand north of Ikoyi Island, and must be accepted with reservation for other mixtures of different porosity and with different sizes of interstitial cavities. However, it is believed that the general principle shown by these experiments is broadly applicable to all sands, although the critical proportions of fine sand or silt causing a rapid fall in permeability may vary according to the proportions in which other grades of sand are mixed.

The relation between permeability and the depth of the black layer in lagoon sands

As sands vary in their composition from place to place, even within distances of a few feet, and permeability, which seems at least to be one of the important factors governing the distribution of the sand fauna, is itself determined by so many interacting factors, a means of estimating the permeability of a sand in the field is clearly necessary. It is possible to reach a tentative estimate of probable porosity of a sand from rough sieving in the field, but a direct measurement of drainage rate through a sand column can only be carried out in the laboratory. In the lagoon sand deposits, as elsewhere, the deeper layers are black with iron sulphide and become yellow on exposure to air or to water saturated with oxygen. It seemed probable that the depth of this black layer is related to the permeability of the sand since its level would be determined by the circulation between the grains of oxygen-rich water from above the sand. In sands of low permeability, and hence poor circulation, the black layer would be near the surface, and where permeability was high and circulation good, the black layer would be at a distance from the surface. It remained to show what relationship exists between permeability, as indicated by drainage time, and the depth of the black layer, as, if this could be interpreted in terms of permeability, a quick and accurate method of measuring permeability would be available for correlation with the distribution of the sand fauna.

A number of different natural sands were chosen in which the black layer occurred at progressively greater depths. The line of demarcation between the upper yellow sand and the lower black sand was very sharp except in coarse sands where the black layer was 10 to 20 cm from the surface. It was found that the best method of exposing this line was to take a trowel full of sand from the intertidal zone at low tide and to break this in two with the hands. The depth of the black layer from the surface could then be accurately measured on the face thus exposed. If measurements were made against a face exposed by a spade or trowel, displacement of the yellow layer due to drag of the spade led to distortion of the line of demarcation. The sands thus chosen in which the depth of the black layer had been measured were then tested for permeability by the drainage method and analyzed. The location of these sands, together with their composition, the depth of the yellow layer above the black and the drainage times, are given in table 6.

A linear relation between the depth of the yellow sand above the black and the drainage time was found as shown in figure 9. This graph, therefore, provides a means whereby the permeability of any of the lagoon deposits in the Lagos area can be determined quickly and accurately in the field from the level of the black layer irrespective of the composition of the sand and the different factors determining permeability. As it is probable that this level was determined not only by the permeability of the sand but also by the oxygen tension of the water above the sand and perhaps by temperature in so far as this may also have affected water movement between the grains, it would be unwise to assume that these figures obtained under tropical brackish conditions necessarily apply in temperate regions. In temperate waters the generally higher oxygen tension alone should give

Table 6

	sieved fractions (%)						drainage time of 50 cm of water through 10 cm of sand	
locality of sand	> 30-mesh	30–60-mesh	60–90-mesh	< 90-mesh	silt	depth of yellow sand layer (mm)	min	sec
Onikan Beach	5	47	41	6	1	5	13	0
Five Cowrie Creek (North End)	12	35	39	13·7	0·3	8	12	40
Onikan Beach	5	48	41	5·5	0·5	15	12	20
Harbour Beach near Five Cowrie Creek	44	22	28	5·93	0·07	48	10	0
Ikoyi Park, North Shore	15	80	4·15	0·6	0·25	150	3	30

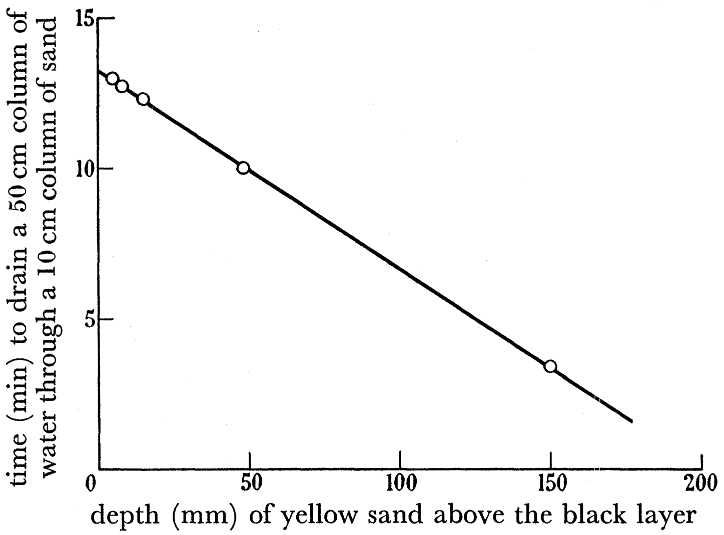

Figure 9. Graph showing the relationship between the position of the black layer and permeability in tropical lagoon sands.

rise to a broader yellow sand layer for a given degree of permeability than obtains in the tropics. It would, however, be expected that the same general relationship should apply to all regions with minor corrections to the slope of the line of the graph in figure 9.

The effects of the fine sand and silt concentrations on the permeability of the deposits given in table 6 are also of interest in comparison with the figures given for additions of those fractions to the North Ikoyi Island lagoon sand (see figures 7 and 8). In table 6 the two sands from Onikan beach were similar in composition except that one contained 0·5 % and the other 1·0 % of silt. In this case, therefore, the difference in permeability can be attributed to the difference in silt content alone. If, however, the drainage times for these sands are compared with those of the North Ikoyi sand with similar proportions of fine sand and silt (figure 8), it is noticed that the drainage times for the Onikan sands were about 2 min slower. It is evident, therefore, that the effect in reducing permeability of a given quantity of silt differs according to the composition of the sand. This can be explained when it is considered that the porosity of the Onikan sands was less than that of the North Ikoyi lagoon sands so that smaller quantities of silt were required to block the interstices. When the sand from the north end of Five Cowrie Creek is compared with the Onikan sands it is seen that they were not greatly dissimilar in composition except that the former contained less silt but more fine sand. The fact that the Five Cowrie Creek sand was intermediate in drainage time between the two Onikan sands suggests that permeability here was controlled rather more by the fine sand fraction than by the silt and that, as already indicated, the effects of both were additive. Finally, the two sands with the most rapid drainage from the harbour beach near Five Cowrie Creek and from Ikoyi Park also indicate the importance of the fine fractions, for these sands clearly owed their good water circulation to a preponderance of coarse grains with low proportions of fine sand and silt.

The selection of sieves for sand analysis

If the texture of sand deposits is to be related to the distribution of the fauna, then it is important that analysis of the deposit by sieving shall be such as to reveal the textural differences to which the various animals react. The sieves used, therefore, should be neither so widely spaced that the grades which they separate cover a range in grain size greater than is necessary to determine the properties of the sand, nor so close that the labour of repeated sieving operations becomes excessive in relation to the information revealed. In the present study the choice of sieves was governed by the mesh sizes readily available and the series used was not necessarily the most appropriate for an ecological survey. It has been shown that, whereas permeability in sands depends on the absolute sizes of grains present, porosity is governed largely by relative differences in grain size. In selecting a series of sieves, therefore, it is important to consider both of these aspects. Since permeability changes so drastically when the size of the grains falls below 0·2 mm in diameter, the 90-mesh to the inch sieve which isolates this fine sand fraction is essential to the series. The sand fraction passing a 60-mesh but retained by the 90-mesh sieve is comparatively uniform and appears to have properties of its own as seen by the importance of this grade in the formation of quick sands. The 60–90 fraction, therefore, evidently does not require subdivision. With the passing 90 and 60–90 fractions fixed it is clear that the subdivision of the coarser sand into fractions should follow the ratio of 1:1·5 between the diameter of the smallest and largest grains in each fraction already set by these two sieves. The analysis of a sand into fractions with a constant ratio between the smallest and largest grains should provide the basis for an assessment of those physical characteristics of the sand on which the distribution of sand-dwelling animals may depend. A recommended series of sieve sizes maintaining an approximately constant ratio of grain size range is given in table 7.

The groupings of particles recommended by the International Society for Soil Science (see Robinson 1932) and the alternative Wentworth Scale chiefly used in America do not fulfil these requirements. In the I.S.S.M. grading the fractions are too wide while in the

Wentworth series, although more divisions are included, the ratio of grain size range between the fractions is not constant throughout. This has probably arisen because the series are based on the size of the coarsest grains (2·0 mm) which has been reduced by a common factor (10 in the case of the I.S.S.M. scale and 2 over most of the Wentworth scale), whereas in view of the importance of the finer fractions it is more appropriate to determine the critical limits of these with respect to the physical properties of the sands and to adjust the gradings of the coarser grains accordingly as has been done in table 7.

TABLE 7. TABLE OF RECOMMENDED SIEVE SIZES FOR SAND ANALYSIS

seive number in mesh to the inch	approximate range in diameter of grains in each fraction (mm) [particles <0·1 removed by washing (silt fraction)]
	0·2 –0·1
90	
	0·3 –0·2
60	
	0·45–0·3
45	
	0·68–0·45
25	
	1·0 –0·68
18	
	1·5 –1·0
12	
	>1·5

SUMMARY

1. The geometrical arrangement of a system of closely packed uniform spheres is considered and the effects on porosity of the addition of smaller spheres to the system determined for comparison with the porosities of various mixtures of different graded sands.

2. The porosity of sands was taken as the weight of water at 25 to 30 °C required to saturate 100 g of dry sand, this method of assessing interstitial space giving more accurate results than the volumetric estimation of the ratio between void and the volume of the grains.

3. The porosity of relatively uniform graded sands was found to be high and of the same order irrespective of grain size. The small difference in porosity in graded sands is related to the shape of the grains and the ratio between the diameters of the smallest and largest grains present, porosity increasing with roundness of the grains and reduction in the grain size ratio.

4. In simple mixtures of two graded sands in various proportions, porosity of the mixture was found to be lower than that of either constituent grade, the extent of the fall in porosity depending on the proportions of the grades present and the ratio of the mean diameters of the grains in the grades. The lowest porosity was obtained when coarsest and finest grades were mixed. In any given mixture the proportions giving minimum porosity are governed by the ratio between the ranges in grain size of the grades. Where this ratio is high minimum porosity is reached when approximately equal proportions of the two grades are present. Where the ratio is low minimum porosity is achieved when 10 to 20% of the finer grade is added to the coarser. When a fine sand is added to a coarse sand some of the small grains occupy the spaces between the large and reduce porosity, while others become wedged between the larger grains and, forcing them apart, cause an expansion of the

lattice formed by the larger particles. The extent to which either of these processes predominates depends on the relative sizes and amounts of the grains mixed. When coarse grains are added to a fine sand, porosity is reduced by displacement approximately in proportion to the quantity of coarse grains present.

5. In natural lagoon sands there is a general increase in porosity with decrease in grain size of the dominant grade present. Sands with a high proportion of rather small, uniform grains are unstable in comparison with those covering a wide range in grain size and do not support populations of burrowing animals.

6. Measurements of capillary lift and the volume of capillary water absorbed by columns of graded sands have been made. The product of the height of the capillary rise and weight of capillary water per 100 g of dry sand is shown to be a function of the grain size. In sand of grain size 2·0 to 0·6 mm the capillary water did not fill all the interstices in the sand. In sands of grain size 0·6 to 0·3 mm and 0·2 to 0·1 mm, respectively, the capillary water saturated the sand. In sand of grain size 0·3 to 0·2 mm, however, the capillary water was in excess of that required to saturate, indicating that the capillary forces were sufficient to expand the lattice of grains and increase porosity. It was demonstrated that increase in porosity due to capillary forces occurred in natural quick sands, but not in firm sands, and was presumably responsible for their instability.

7. The rate of evaporation of water from different grades of sand was measured to give an indication of the proportion of contained water held by surface forces. It was found that in sand of grains 2·0 to 0·6 mm in diameter the rate was similar to that from a free water surface and there was no check to evaporation as dryness was approached. In finer sands evaporation was noticeably slower and was checked as dryness approached showing that up to 14 % of the contained water in sand of grains 0·2 to 0·1 mm in diameter was held by surface forces, and thus was not available for free circulation between the grains.

8. A method is described for the measurement of the rates of drainage of water through sand as an indication of permeability.

9. In a series of tests on different sand fractions it was found that whereas drainage through sands of grain size greater than 0·2 mm was comparatively rapid, not exceeding 11 min for a 10 cm column of grains 0·3 to 0·2 mm in diameter, the drainage time through grains 0·2 to 0·1 mm in diameter was more than 25 h.

10. The addition of sand of grain size 0·2 to 0·1 mm in increasing quantities to a natural lagoon sand caused a decrease in drainage rate, the point of inflexion of the parabolic curve representing drainage time against percentage of fine sand present occurring at about 25 % of fine sand. The drainage times, however, did not approach that of the fine sand alone so that the mixture is envisaged as a lattice of large grains with the spaces tending not only to be filled by small grains but also enlarged as some of these grains wedge the large grains apart.

11. It was also found that a similar decrease in drainage rate occurred when silt was added to the natural sand, the point of inflexion of the parabolic curve of drainage time against silt concentration in this case occurring when 1·4 % of silt was present. It is suggested, therefore, that critical concentrations of fine sand and silt are likely to be about 25 and 1·5 %, respectively, where the circulation of water in the sand is important to burrowing animals for their oxygen supply and the removal of waste products.

12. The distribution of lancelets in the Lagos area has been shown to be limited by the permeability of the sand deposits, lancelets tolerating up to 25 % of sand grains under 0·2 mm in diameter or up to 1·5 % of silt.

13. It has been shown that the depth of the black layer in lagoon sands is directly related to the permeability of the sand as indicated by the drainage time, thus providing a method whereby an accurate estimate of the permeability of sand can be made in the field.

14. A new scale of sieves is recommended for the analysis of sand samples in ecological surveys.

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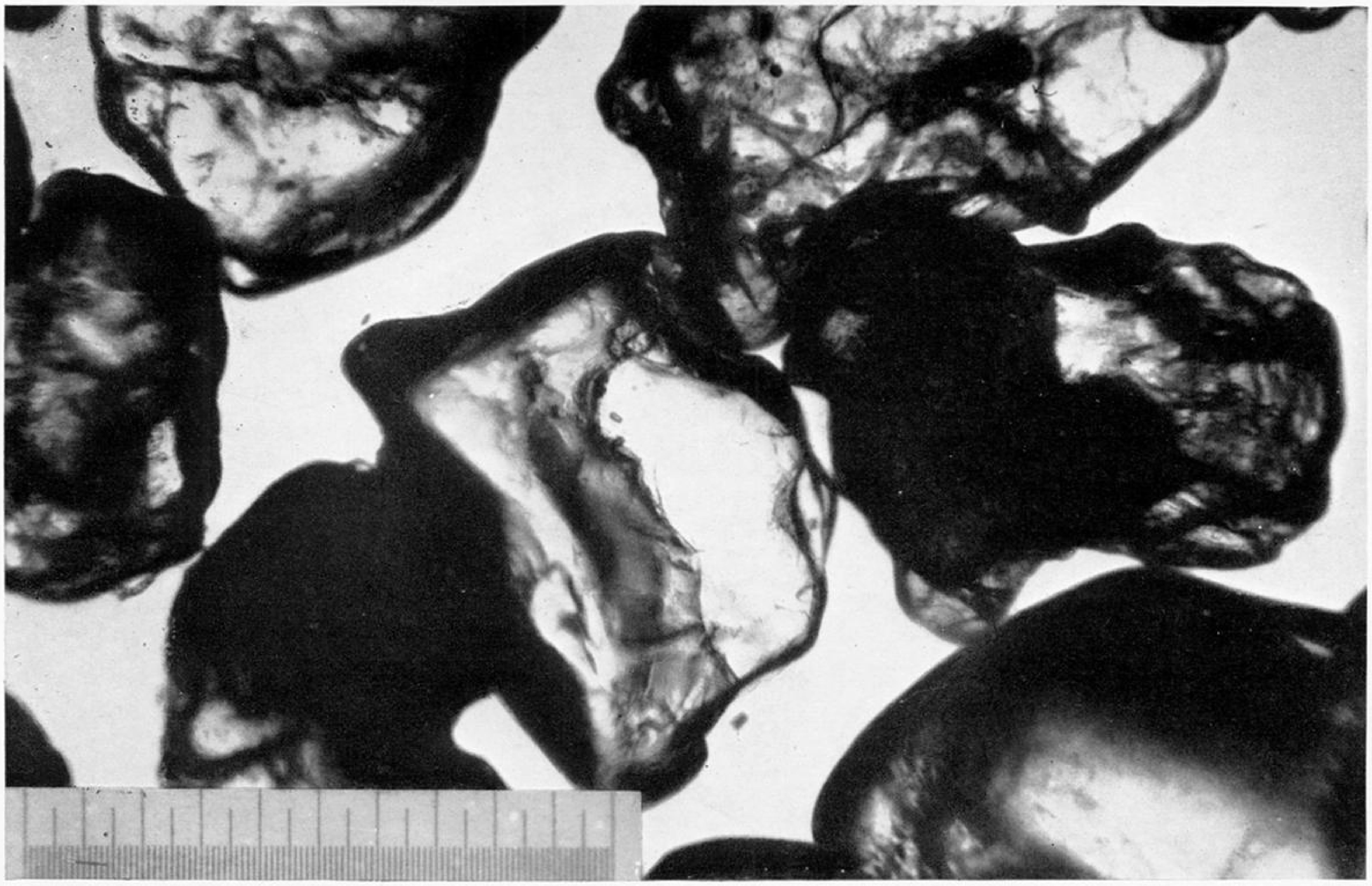

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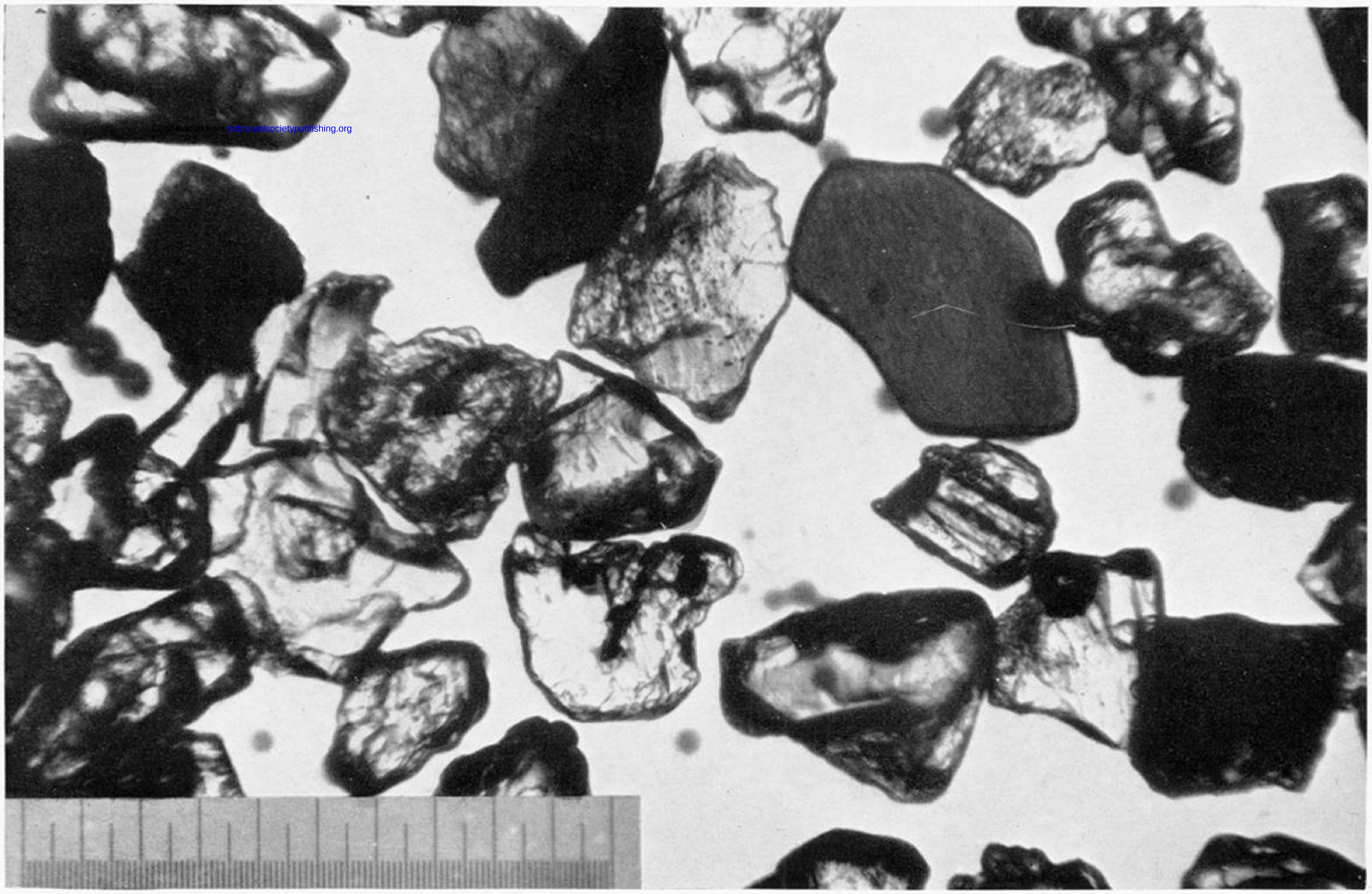

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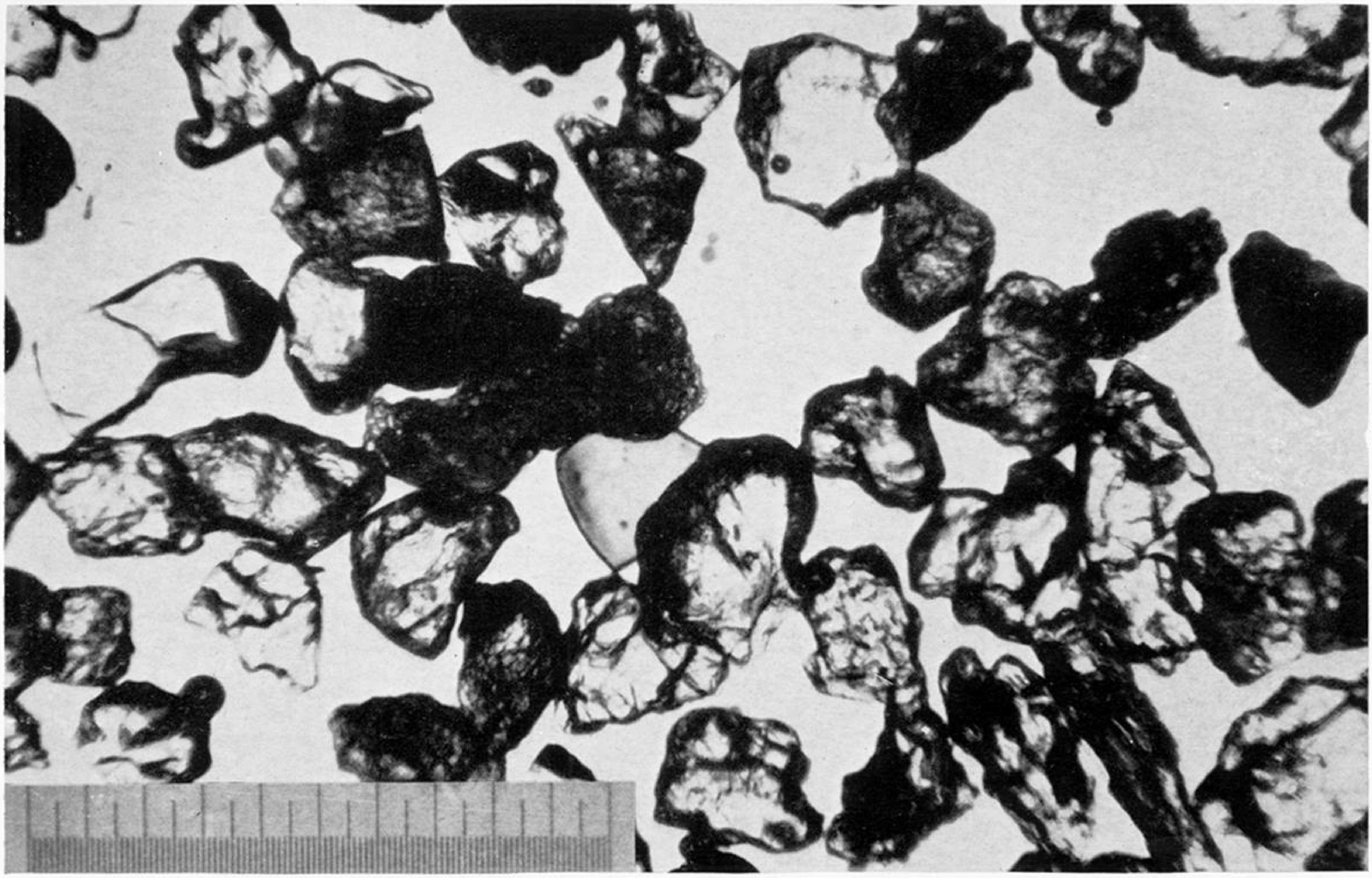
IGURE 10. Sand grains retained by a 30-mesh/in. sieve. Scale length 1 mm.

IGURE 11. Sand grains passing a 30-mesh but retained by a 60-mesh/in. sieve. Scale length 1 mm.



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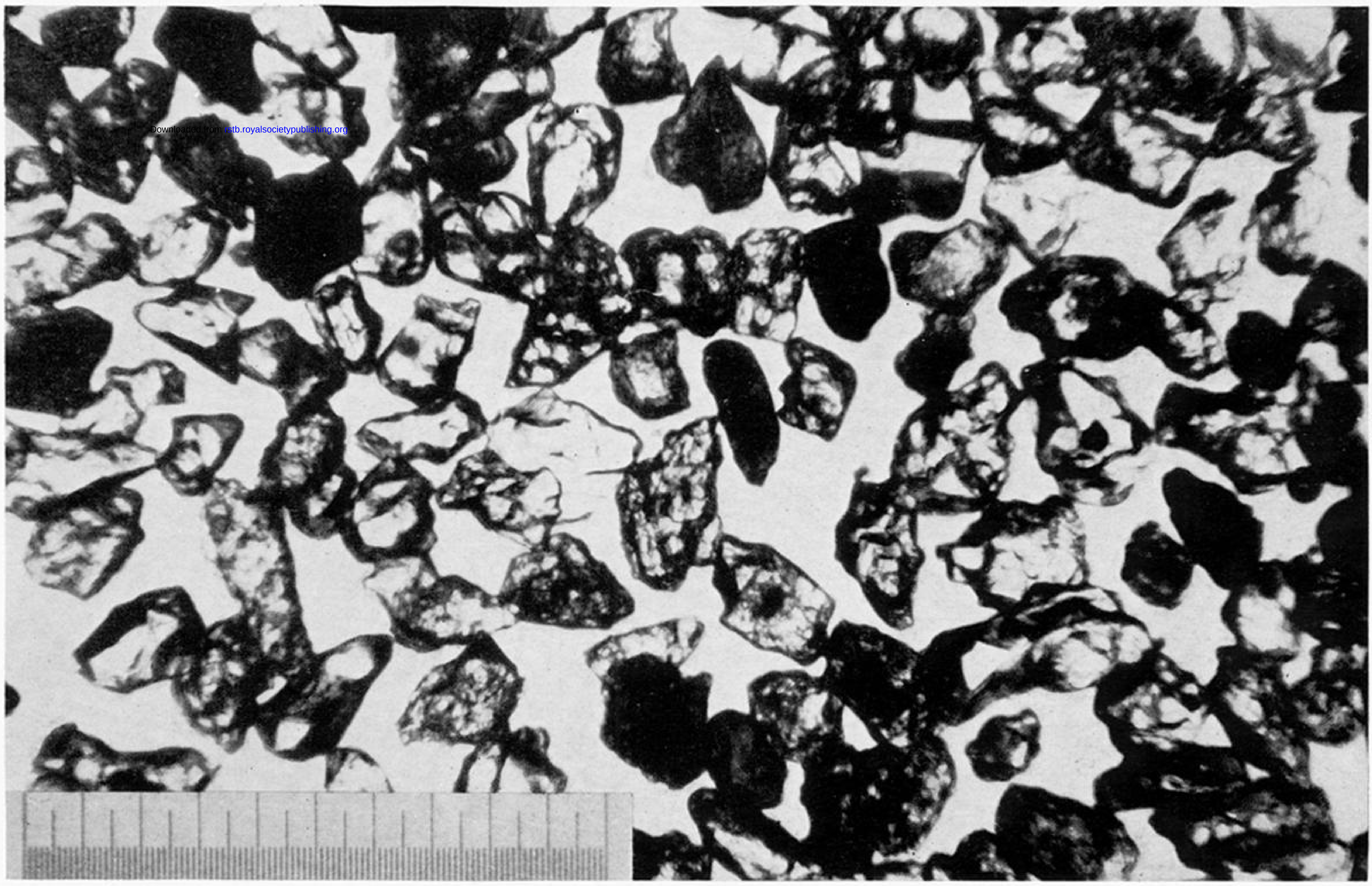

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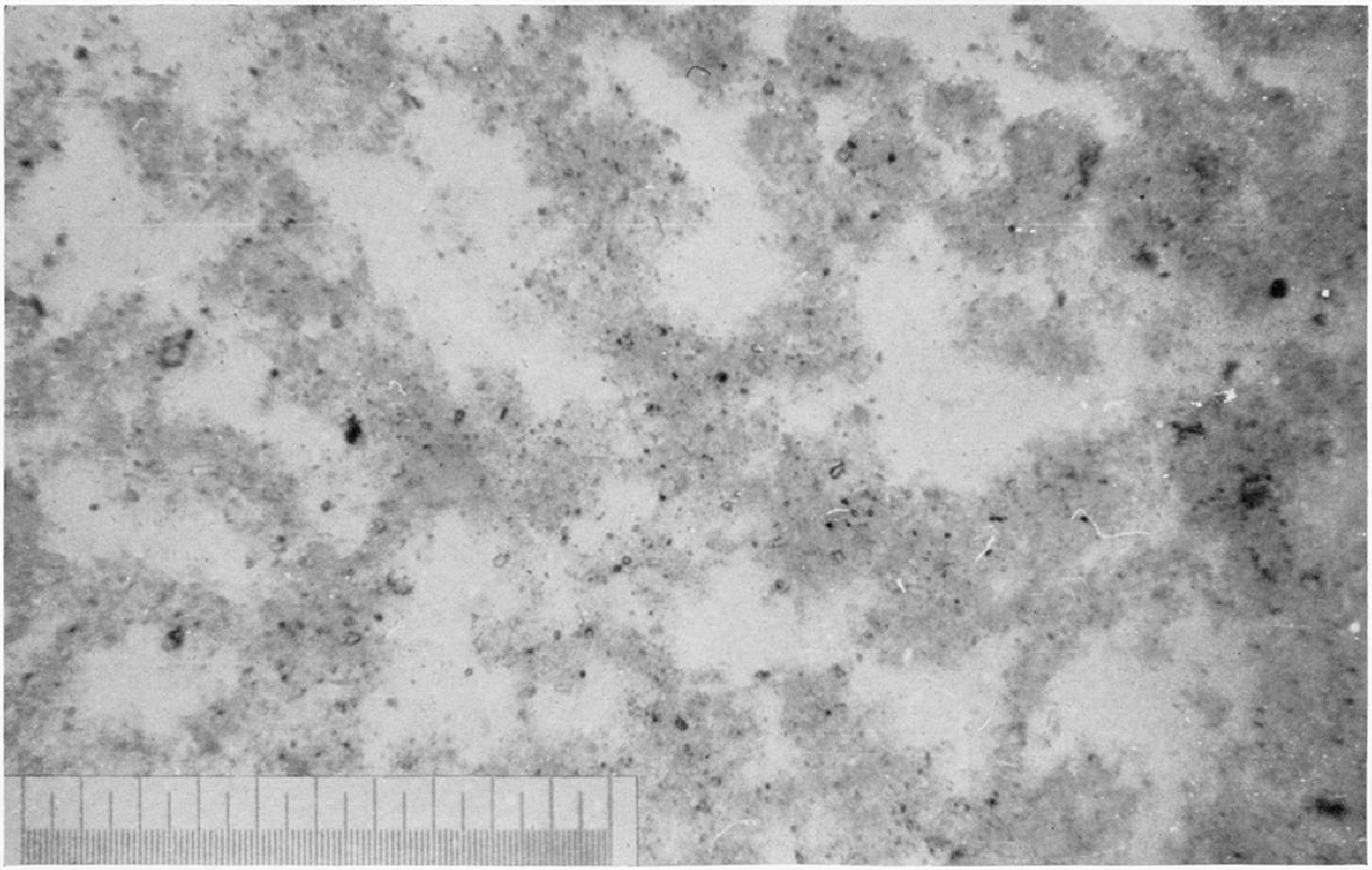
IGURE 12. Sand grains passing a 60-mesh but retained by a 90-mesh/in. sieve. Scale length 1 mm.

IGURE 13. Sand grains passing a 90-mesh/in. sieve. Scale length 1 mm.



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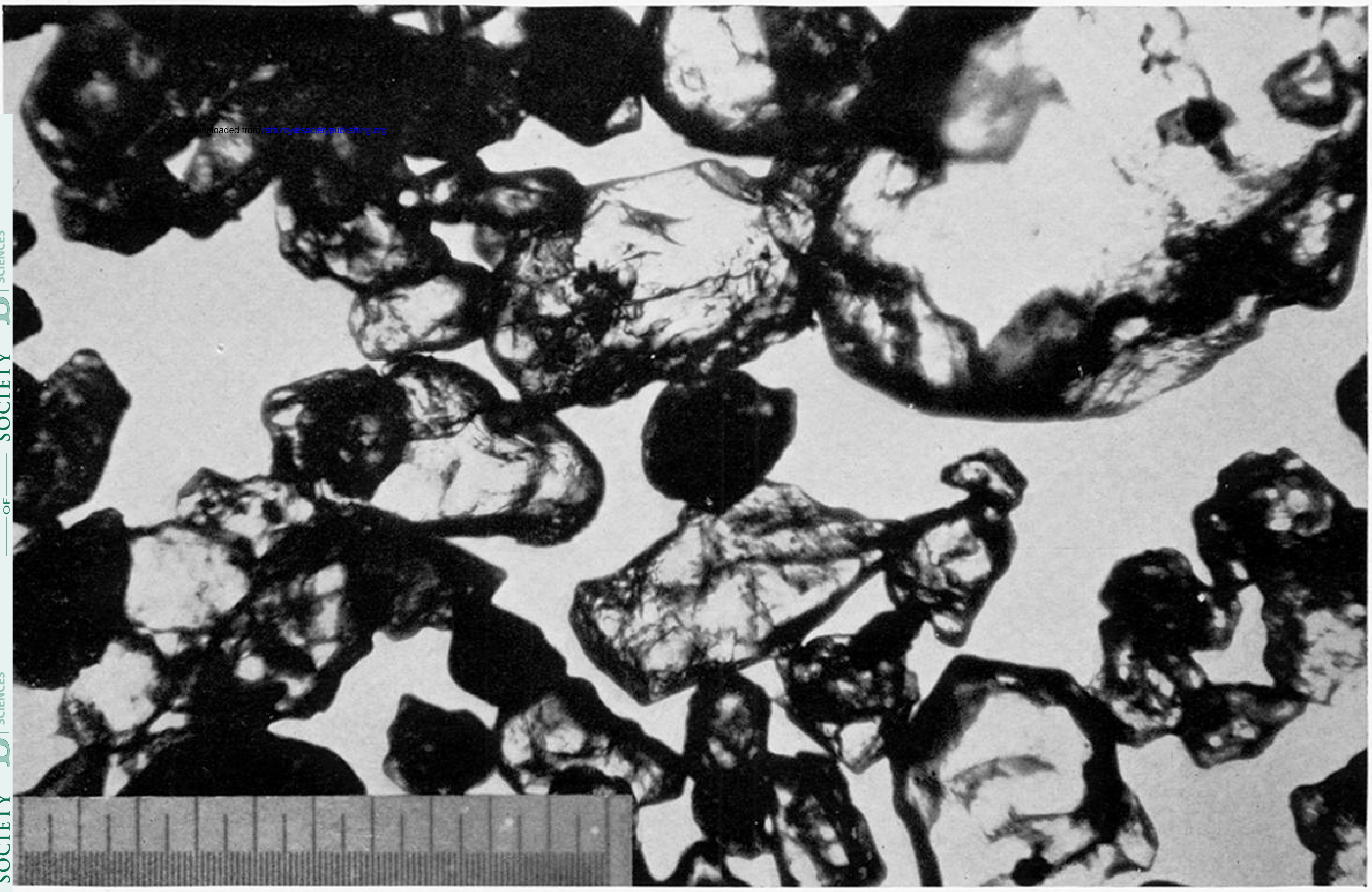

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IGURE 14. Silt extracted from lagoon sand. Scale length 1 mm.

IGURE 15. A natural sand from the lagoon north of Ikoyi Island, Lagos. Scale length 1 mm.