ON THE LAWS GOVERNING SEDIMENTATION FROM EOLIAN SUSPENSIONS

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1. INTRODUCTION

Research history shows that the first to study the general physical and geological laws governing sedimentation from eolian suspensions was UDDEN (21). In his paper published at the end of the last century, this author treated the grain size distribution of dust and detritus caught up by air currents in a mostly descriptive, compilative manner. His work was considerably extended in the direction of pragmatism and experimentation by KÖLBL (8, 9), who determined the fall velocity of particles in air, as well as the interdependence of fall velocity and the grain size of the deposited sediment. However, the work of these two scientists did not ripen into a comprehensive interpretation that would have granted a full insight into the topic.

Our detailed studies in sedimentary petrography made it a necessity to inquire into every one of the interwoven phenomena playing a part in deposition, for in the lack of considerations of this kind none of the basic problems of the process can be correctly interpreted, not even the role of fall velocity.

In a paper published in 1956 (16), the problems of the velocity of settling, movement and sorting of the falling particles were already discussed by the present author in a number of respects. However, in the mentioned study no complete synthesis was arrived at, either, because the study of the interrelations of eolian and fluviatile deposition was missed; neither was the process of internal sorting due to transportation at high altitudes cleared. However, it was just by these considerations that the general laws of deposition of suspended dust could be elucidated. The present paper has the aim of summarizing the results achieved so far by the present author, and published in his earlier papers, concerning the process of deposition from eolian suspensions, and of subsuming these results under a uniform point of view.

The most generally studied property of mechanical sediments is their grain size distribution, a feature which stands in a close relation with a number of their physical properties and is one of the most important indicators of their ways of formation. Concerning the grain size distribution of e. g. the finer fluviatile deposits, we have generally accepted notions of long standing of which excellent use can be made when the genesis of some sediment of this type is to be determined. The grain size distribution of the loess of eolian genesis is another well-known characteristic, the interpretation of which is, however, still lacking. Even the problems of the stratigraphic role and of the genesis of loess depend on the correct recognition of its mechanism of deposition. In the opinion of some, loess could not possibly have in this country under the climatical conditions of some phases of the Pleistocene, namely simultaneously with wind-blown sand, whereas others assert that loess is a heteropic facies of wind-blown sand and that both come from a nearby source. The decision of this problem, too, must be based on research into the laws governing the deposition of the sediments in question: we must study the interrelation of the grain size distributions of eolian dust and wind-blown sand, we must establish numerical relations between the grain size distributions of the rolled and suspended fractions blown out of some accumulation of detritus.

As an introduction, let us consider the fall velocity and the floating properties of the sedimentary particles; then we shall pass on to the study of the facies relations of the grain assemblages, that is, of the sediments and trace them throughout the process of sedimentation.

2. THE RELATIONS GOVERNING FALL VELOCITY IN STAGNANT AIR.

According to investigations by Kölbl (8, 9) the fall velocity in air of grains of different size varies as the diameter of the grains down to a diameter of 0,05 mm. However, grains smaller than that drop considerably slower. This means that, to keep up suspended particles under 0,05 mm, a disproportionately slower air motion is sufficient than for particles above this size; that is, the particles of the dust fraction are fairly liable to remain in suspension for long periods. The table below lists the diameters and fall velocities of the grains, partly as determined by newly performed experiments.

Diameter mm	*fall velocity cm/sec*
0,01	2,8
0,02	5,5
0,05	16
0,06	50
0,1	167
0,2	250
2,0	500

The data concerning the grains above 0,06 mm diameter were taken from Kölbl's work whereas those for the smaller grains were experimentally determined by the present author. The experiments were performed in the following way.

Grain size fractions of 0,005—0,01, 0,01—0,02 and 0,02—0,05 mm diameter respectively were separated by the *Atterberg* method of washing. After drying, the particles were sedimented in air in a tube of 1 metre length ending below in a glass cylinder. The grains were introduced by smearing a very small amount of the preparate onto a sheet of paper which was subsequently placed over the upper end of the tube, with its smeared face down. The particles were propelled into the tube by a single pat on the paper. The settling velocity was then measured through the glass cylinder, under appropriate illumination.

The results were checked by a different method. The sample was introduced into an open paper tube of 1 m length and after the elapse of 3, 4, 5, 10 and 20 minutes, respectively, a sheet of black paper was slid under the bottom end of the tube. The size of the particles settling onto the black paper was measured under the microscope. *(Fig. 1.).*

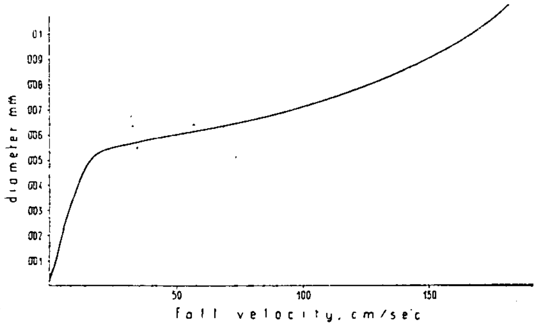

Fig. 1.

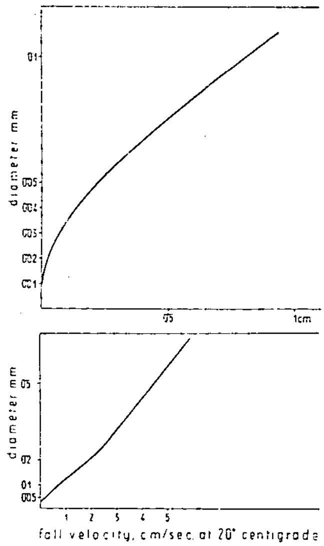

Fig. 2.

Let us note that a fall velocity graph of similar trend is obtained if KÖLBL's data only are plotted. Extrapolating his curve beyond the point of 0,06 mm grain size to the zero point, we have a graph that does not differ in principle from the above one. Hence, KÖLBL was certainly in a position to establish the principal difference between settling in water and in air, without any further measurements; he did not mention any result of this nature, though. On the contrary, he reached the conclusion that the sharp break occurring in air at the grain size of 0,05 mm is analogous to that occurring at 0,02 mm in water. However, the inspection of STOKES's settling-velocity table and of the digram constructed therefrom for water clearly shows that the mentioned section of the graph is almost straight and exhibits no sudden increase of the floating ability. *(Fig. 2.).*

Fig. 3. shows the settling velocity in air of particles from o to 2 mm.

The argument becomes even more convincing if the settling velocity of the grains of a given dimension is compared to that of the grains smaller by one hundredth of a millimetre. Thus for instance the settling velocity of the grains of 0,05 mm diameter is 16 cm/sec, whereas that of the grains of 0,06 mm size is 50 cm/sec. $50/16 = 3 \cdot 1$, or, in words, the floating ability of the grains of 0,05 mm size is 3,1 times as great as that grains of 0,06 mm size. For the grain size of 0,06 mm this ratio is 2 (that is, the floating ability of the grains of 0,06 mm size is twice that of the grains of 0,07 mm size); for the grain size

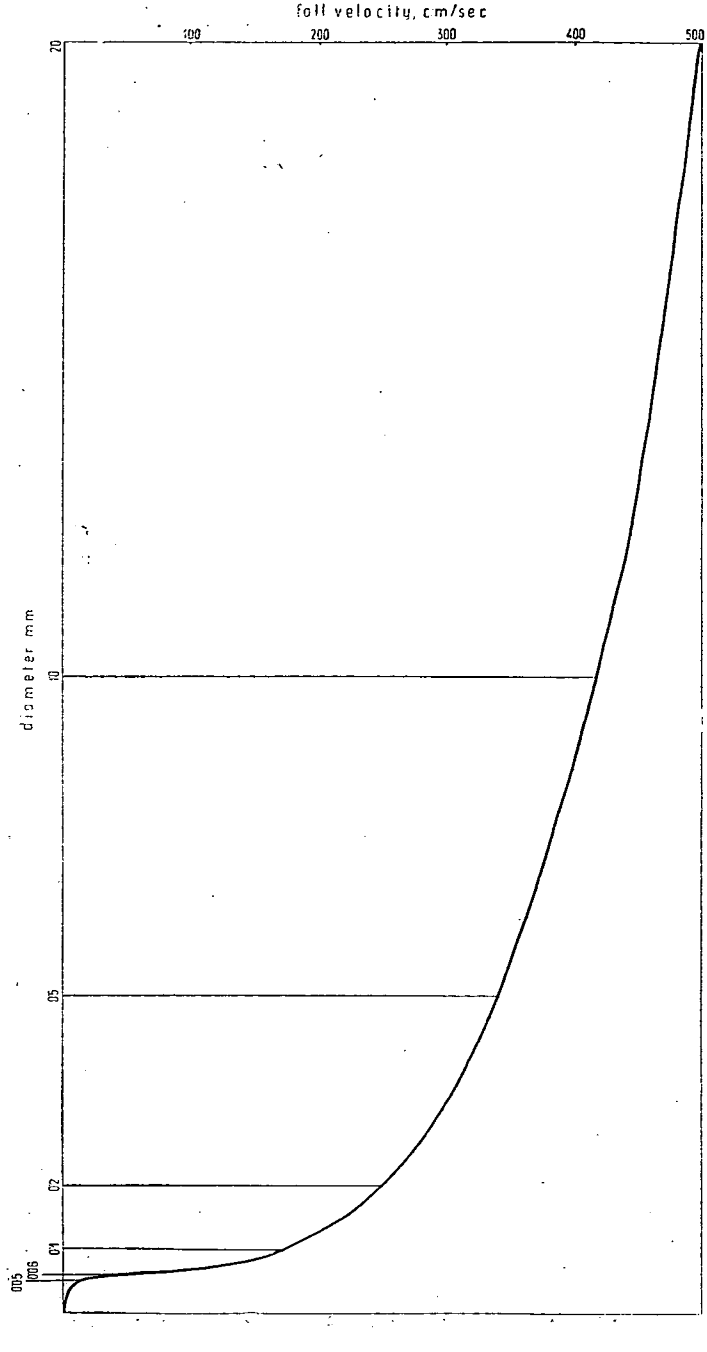
foll velocity, cm/sec
100
200
300
400
500
diameter mm
20
10
05
02
01
006
005

Fig. 3.

of 0,04 mm it is about 1,4. The results are shown by *Fig. 4.* For the sake of comparison, we have presented also in this case the appropriate ratios for grains settling in water. *(Fig. 5.)*

In air, the peak at 0,05 mm divides the grains into two fractions of particularly good and particularly poor floating ability, respectively. *(Fig. 4.)*.

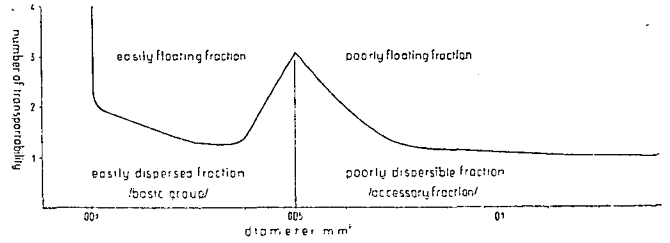

Fig. 4.

The grains below this limit drop at a rate of *at most* 16 centimetres, those above at a rate of *at least* 50 centimetres per second. The figure shows further that around 0,05 mm even a slinght change of diameter results in a considerable change of the fall velocity.

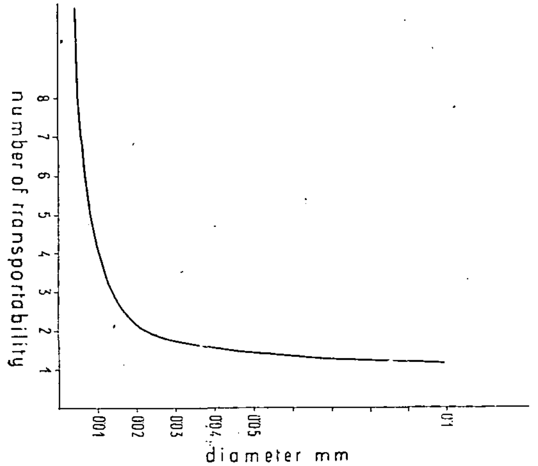

Fig. 5.

The behaviour of the two groups is characteristic also as regards the dispersion effected in the course of transport and settling. The grains of fair floating ability are widely dispersed and conversely. In the light of this recognition it shall be possible to trace the evolution of the grain size distribution of both the suspended fraction and the fraction travelling close to the ground. As regards numerical values, we shall return to this point later on.

This peculiar feature of the settling-velocity diagram clearly reflects a property of the drag of the medium. The obvious reason for the sudden increase of the fall velocity in air at the grain size of about 0,05 mm. is that the drag of the medium decreases at a disproportionate rate with the increase of the diameter, that is, of the mass of the particle. *(Fig. 6.).* A change of diameter from 0,05 to 0,06 mm is equivalent to an increase of mass by round 70 percent, whereas the settling velocity and consequently the drag of the medium increase in the same interval by 210 percent!

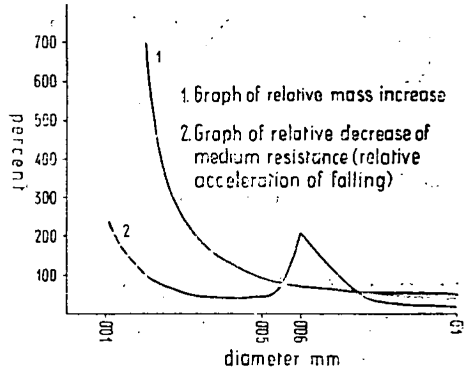

Fig. 6.

Concerning the rest of the grain size groups we have the following relations:

Change of diameter, from 0,01 to 0,02 mm	Increase of mass, percent	Increase of settling velocity or decrease of drag of drag of medium, percent
	700	
„ 0,02 „ 0,03	237	90
„ 0,03 „ 0,04	137	51
„ 0,04 „ 0,05	95	39
„ 0,05 „ 0,06	70	39
„ 0,06 „ 0,07	60	210
„ 0,07 „ 0,08	50	96
„ 0,08 „ 0,09	43	29
„ 0,09 „ 0,1	37	18

If the density of the grains is increased instead of their diameter, a similar drag diagram results. In essence, both the increase of the grain diameter and of the density result in an increase of the downward-moving force, the force of gravity acting upon the grain. It follows hence that, should the gravity acceleration on the Earth surface increase to twice its present value, the critical grain size would be shifted towards a particle mass half as great, that is, towards the diameter of 0,04 mm — always provided that the density of the air would remain the same. In the above case the upper grain size limit of ideally sorted loess would be 0,04 mm instead of the actual 0,05 mm. An increase of the gravity force to ten times the present value would entail a shift of the critical limit to 0,023 mm, a decrease of the same order a shift to 0,11 mm. Consequently, a gravity force ten times greater would have resulted — assuming that the dust was blown out of an aggregate containing relatively few removable, unbound grains of 0,01 to 0,02 mm diameter and that the air density remained unchanged — in the formation of considerably less and considerably better-sorted loess than was the case in the Pleistocene, since the fraction of 0,02 to 0,05 mm diameter, constituting the bulk of Pleistocene loess, would have entered the wind-blown sand fraction, owing to the poor floating ability of the grains. On the other hand, a gravity force less by ten times would have entailed the formation of much more and much worse-sorted loess. This circumstance will have to be taken into account when considering the eolian dust deposits formed in the ancient gravity field of the Earth which was possibly of a different strength. *(Fig. 11.)*. It is to be emphasized that in our computations we have left out of consideration the change of volume and taken the change of mass only. *Fig. 6.* is thus, as a matter of fact, a diagram of mass or diameter *vs.* drag and thus not wholly coincident with the curve of density *vs.* drag.

The point at which the fall velocity takes a sudden increase is to be considered a characteristic physical parameter of the medium in which falling occurs.

3. THE RELATIONS GOVERNING THE VELOCITY OF PARTICLE MOTION IN MOVING AIR.

If in the course of settling the air moves upward at the same speed at which the particles would fall in stagnant air, the particles will evidently keep on floating at constant altitude. Consequently, a particle floating at constant altitude must be moving at its characteristic fall velocity with respect to the gas molecules. The particle is kept at constant altitude by the drag of the gas molecules moving upwards; the latter impart to the particle their kinetic energy in the course of innumerable collisions and thus neutralize the downward pull of the gravity force.

It is obvious that in nature there exists no durable vertical current of this kind. However, the streamlines of every turbulent current can be resolved into horizontal and vertical displacements, and thus every eddy and the whole turbulent current can be put together out of such elementary components. The present treatment of the hypothetical vertical air motion, an attempt at a general characterization, is to be extended in the following also to the general case of oblique air motion. In this way we shall be able by the aid of observations and deductions to approximate some of the basic principles of the mathematical theory of particle motion in currents.

In summary, the speed of the ascending air current necessary to keep the particles floating at constant altitude is just their fall velocity in stagnant air. At the same time, this is the least velocity sufficient to lift the particle off the ground. A stream of smaller velocity is unable to move the particle, whereas a swifter current will keep on lifting the grain to ever greater altitudes.

Even in stagnant air, the fact that the particle falls at constant speed instead of being constantly accelerated by the gravity force is due to the drag exerted by the molecules. The settling particle collides with enormous numbers of gas molecules, and although the latter are easily pushed aside, owing to their minute mass, they nevertheless have a braking effect on the grain of dust. With the increase of the fall velocity, the collisions with the gas molecules become more vehement, so that an equilibrium is established between the downward pull of the gravity force and the drag („friction") of the molecules, and from there on the fall velocity remains constant.

The case is different if the air moves upward at a rate lower than the settling velocity of the particle. In this case the collisions with the molecules are insufficient to keep the particle at constant altitude wherefore it commences slowly to sink. The relative velocity of the particle with respect to the air current remains the same (this is the condition for constant fall velocity), but the resultant velocity composed of the air motion and the falling of the particle with respect to the air current will now have a downward component.

If the velocity of the upward current is greater than the fall velocity of the particle, the latter will keep on rising, although it is invariably moving downwards with respect to the gas molecules. In the case of very fine dust and very great current velocity the rate of rising of the particles will practically reach that of the air current.

After the beginning of the process of settling, the velocity of the particle and the drag of the molecules change from zero to a certain value which remains constant in the course of the further history of the process. This constant speed may be widely different if related to the ground, but it is always the same as related to the gas molecules. Thus, the rising of the air current is invariably swifter than that of the suspended particle. As a result, there is no mixing of particles of identical size, and even the mixing that takes place has a direction different from that of the gas molecules, as will be expounded later.

The above considerations concerning the motion of dust particles were referred to the rather narrow case of the vertical air current. Now there arises the question as to what makes the wind, felt to be blowing horizontally, capable of lifting and transporting dust particles. This ability is due to the fact that wind is a turbulent, eddying current, whose streamlines have also vertical lifting components. However, as the air motion in the turbulent current is predominantly horizontal, we must now direct our attention to the lifting power of obliquely streaming molecules.

The effect of an air current rising at an angle other than vertical, the displacement of the particle can be determined by a simple construction of vector composition. For instance, to keep floating a particle of 0,05 mm diameter, a vertically rising air stream of the velocity $v_1=16$ cm/sec is necessary. If the angle of ascent of the air current decreases to 45° as measured against the horizontal plane, the velocity must increase to 22.6 cm/sec to keep the particle at constant altitude. In the process, the particle will be displaced also horizontally, namely by the amount of 16 cm a second. *(a_1.) (Fig. 7.).* The displacement of the trajectory of the particle as related to the trajectories of the air molecules is 22,6 cm *(b_2)*. However, this displacement does not equal the actual displacement of the particle against the molecules, as was the case with the vertical air current, *(b_1)*, since the particle will, owing to the horizontal component of the motion, be dragged along to a certain extent by the molecules. The flatter the angle of ascent of the air current, the greater the horizontal component of the motion belonging to the same value of the vertical component, that is, the greater the current velocity necessary to keep up the particle *(v_2, v_3)*; however, the relative displacement of the particle against the molecules *(k)* is unchanged. The figure indicates that in a strictly horizontal air motion the particles retain their altitude only in the practically impossible case of infinite current velocity; nevertheless, in an exceedingly swift horizontal air current the streamlines and the trajectories of the particles will practically coincide, and also the velocities of the two bodies will be practically equal.

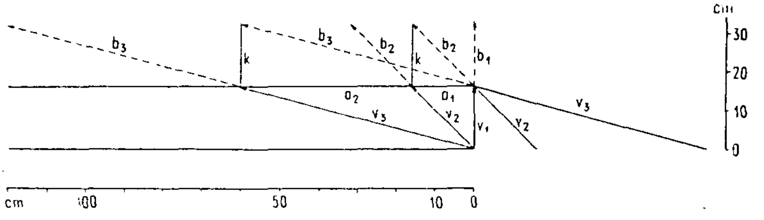

Fig. 7.

If the angle of ascent of the current is less than 90° and its velocity greater than the minimum needed to keep up the dust particles, the latter will always rise along trajectories slightly flatter than the streamlines. (Line *c* of *Fig. 8.).* The two paths will coincide only in the case of infinitely great velocity or of very small particles.

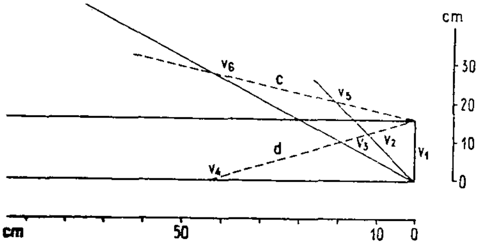

Fig. 8.

If at a given angle of ascent the velocity of the air current is less than the critical value, the particle will settle along an oblique trajectory. (Line *d*). The latter is the nearer the vertical, the smaller the velocity of the stream. The rising or falling trajectories of the particles may coincide even if the angle of ascent of the current varies, provided its velocity varies accordingly. (See the point of intersection of the lines *c* and *d*.)

Fig. 9. represents the trajectories of grains of different size under identical streaming conditions. The current rises at an angle of 45°, at velocities of v_1 and v_2, respectively. In the case of the velocity v_1, a particle of 0,06 mm diameter proceeds horizontally, particles ranging from 0,02 to 0,05 mm are

rising, whereas particles of 0,1 mm size are dropping at a steep angle. It the current velocity increases to v_2, all particles begin to rise except those of 0,1 mm diameter which move in the horizontal.

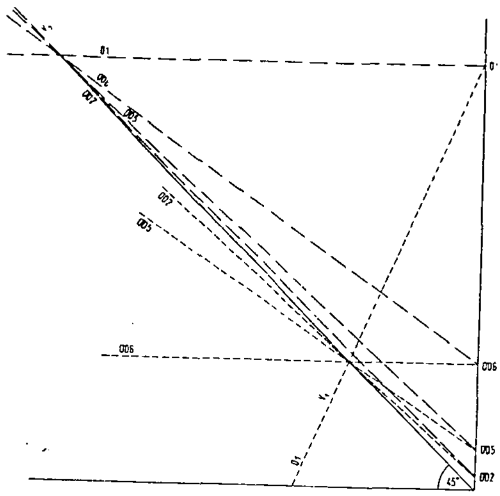

Fig. 9.

Since in nature both velocity and direction of the current are in a constant change, complicated trajectories are being realized in the process of transport. However, the essential point is that even a turbulent stream cannot exert a lifting force except if it attains the critical velocity corresponding to its angle of ascent. Furthermore, a durable transport can take place only if this state of things is itself durable, that is, if it is repeated at an appropriate frequency through an extended interval of time. The question as to what current velocity is necessary to exert such a lifting force, as well as the problem of the relation lifting power vs, wind velocity can be answered only by experience. Mesurements imply that suspended systems containing particles of 0,1 to 0,2 mm besides the dust fraction have been carried to considerable distances by winds of 15 to 20 cm/sec velocity.

4. SPATIAL RELATIONS OF BLOWOUT, TRANSPORT AND DEPOSITION.

After having been blown out from some accumulation of debris, a grain aggregate of mixed size is separated into a readily floating, mobile finegrained fraction whose settling is opposed by a considerable drag of the medium, and into a coarser-grained fraction generally moving along by rolling along the surface of the Earth. The tracing of the history of the two fractions and the changes of state of the depositing medium throughout a single elementary phase of sedimentation leads one to the following conclusions.

The rolled fraction is characterized by the following features: it moves in the plane of the relief, it possesses a well-defined kinetic energy and there is a direct relationship between the distance traveled and the energy consumed by the motion; owing to friction, the rolled particles come to an immediate halt as soon as the moving force ceases. Hence, the distance traveled can be determined if the transporting energy is known.

On the other hand, the floated fraction is lifted off the ground, whereby it gains besides its kinetic energy also a certain amount of potential energy. The fact that the floated particle is in possession of both kinds of energy has the consequence that the floated fraction cannot possibly settle in the zone across which it is transported. Between the distance travelled and the moving energy there is no direct relation; the motion does not cease as soon as the moving energy is spent. The potential energy is equivalent to a certain altitude, equalling in our case the altitude attained by the floated fraction in the course of its transport. This is the altitude that, after the air motion ceases, defines the layer of air to be termed the zone of depostition.

The significance of the zone of deposition is especially clear in the case of grains of good floating ability. After the immediate drop-out of the coarser grains, the settling of the dust particles takes place even in totally immobile air at a rate at least three times, and under a grain size of 0,02 mm even 17 times slower than that of the coarser grains. In consequence, dust-bearing and dust-free zones are developed in the transporting medium. The conditions are made clear by *Fig. 10.*

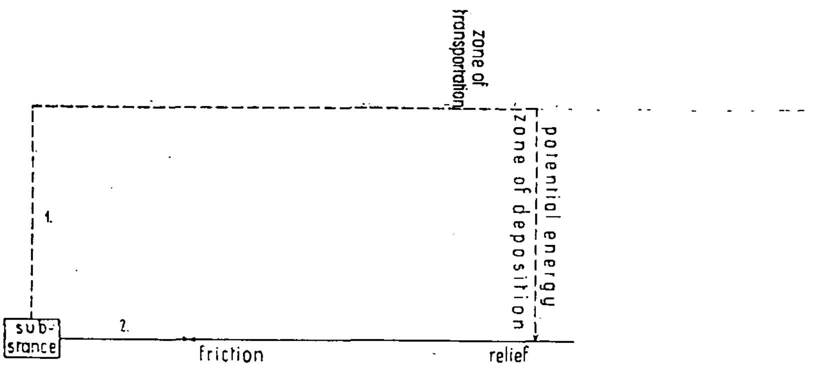

Fig. 10. 1. Path of suspended fraction.
2. Path of rolled fraction.

Of course, this sketch is no attempt at showing the actual path of the transporting wind or at the simplification of atmospheric phenomena. It only presents the elementary consequences of the process of transport. The trajectories realized in nature depend upon the caprices of the atmosphere, but they do not affect the final results. The most important condition for dust accumulation is the development of a zone of deposition, in the broadest continental as well as in the narrowest local relation. Now this condition may be satisfied under widely different atmospheric circumstances. Two main types of the possible atmospheric conditions were already recognized by Z. RÓNA (17, 18) in connection with the dust depositions in the years 1896 and 1901. In his opinion, the dust deposition of the year 1896, whose dust material is thought to have arrived from the sand steppe Deliblát, was due to an exceptionally vehement storm in that region. The dust was carried away by the outblowing wind and deposited later mostly in Transdanubia. Consequently, in this case, although from the aeronomical point of view these three processes took place within a single atmospheric domain, in the sedimentological sense we must distinguish several zones within this unit, the dimensions and properties of which were determined by the vehemence of the blowout, the force and direction of the air current etc.

On the other hand, in the case of the dust deposition of 1901 whose material was of Saharan provenience, transport was effected in RÓNA's opinion only in the first phase of the process by the outblowing wind. The dust, lifted to considerable altitude, was taken over by a high-altitude wind system, independent of the previous one. The trajectory of the particles did not essentially differ from the one described above, but here the zones of transport and deposition could be distinguished also on an aeronomical basis, since the limit of the two zones coincided with the limit of two independent wind systems.

5. THE FACTORS GOVERNING THE SORTING OF SUSPENDED MATERIAL IN AIR AND WATER.

Of decisive significance for the further treatment of eolian sedimentation is the paradoxical fact that the suspended matter, the floating dust not infrequently carried to distances of several thousand kilometres, attains but seldom such a high grade of sorting as would be expected in the knowledge of the essential differences in settling velocity. There occur in the grain assemblage besides the fraction below 0,05 mm also coarser grains. It is a quite general case that the finer grains are accompanied by numerous particles ranging from 0,05 to 0,1 mm, frequently even by some grains up to 0,5 mm. These, although in a steadily decreasing percentage, follow the fraction under 0,05 mm all the way in a number of instances.

The table below shows the grain size distribution of one of the dust samples of the fall at Szeged in 1941, as determined by I. MIHÁLTZ (14). (Szeged, the roof terrace of the University building.)

0,0— 0,0005	0,0005— 0,001	0,001— 0,002	0,002— 0,005	0,005— 0,01	0,02— 0,02	0,02— 0 05	0,05— 0,1	0,1— 0,2	0,2— 0,5	mm Ø
1,01	2,8	4,03	4,87	6,99	16,0	58,0	3,07	2,33	0,85	weight per cent

According to SCHAFARZIK, the dust settled in 1901, also mostly of Saharan origin, consisted predominantly of grains of 0,013 to 0,04 mm size, but a few grains were close to 0,067 mm, whereas in the sample from Váchartyán even a particle of 0,11 mm diameter was encountered. (19). Becke has published a table on several dust samples fallen in Austria at about the same time. The table presented the predominant and the maximum grain size. It is reproduced below together with the data of Häpke from Bremen, of Barac from Fiume and of Schafarzik from Váchartyán.

Locality	Predominant fraction Ø mm	Maximum grain size
Kufstein	0,001 — 0,03	0,08
Zell am See	0,001 — 0,02	0,08
Judenburg	0,001 — 0,03	?
Greifenburg	0,001 — 0,03	0,13?
Arnoldstein	0,001 — 0,025	0,05
Kirchbach	0,001 — 0,032	0,1
Pontafel	0,001 — 0,03	0,11?
Tarvis	0,001 — 0,03	0,07
Görz	0,001 — 0,025	0,075
Lessina 1901	0,001 — 0,02	0,07
Lessina 1879	0,001 — 0,03	0,07
Bremen	0,001 —	0,1
Fiume	0,001 — 0,051	0,113
Váchartyán	0,0013— 0,04	0,11

These analyses were performed by counting out the grains under the microscope. No weight percents were calculated, wherefore the predominant grain size fraction is displaced somewhat towards the 0,001 mm diametre; the number of the grains is greatest in that fraction. A similar distribution is obtained, however, if the latest mechanical analyses of wind-transported dust are recomputed to yield grain numbers instead of weight percents.

Finally, let us cite an eolian dust analysis likewise performed with up-to-date techniques: that of Swineford and Frye (20) performed on a sample from Kansas (1939).

0,0— 0.00098	0,00098— 0.00195	0,00195— 0.0039	0,0039— 0.0078	0,0078— 0.0156	0,0156— 0.0312	mm Ø
5,55	2,67	5,31	3,89	5,63	24,41	weight per cent

0,0312— 0.0625	0,0625— 0.0125	0,125— 0.25	0,25— 0,5	0,5— 1.0	1,0— 2.0	mm Ø
41,85	8,45	1,64	0,38	0,19	0,04	weight per cent

Consequently, the majority of eolian dusts, even the very well-sorted and most carefully collected samples, indisputably contain grains larger than 0,05 mm. In this connection there arises the problem as to why in the majority of cases no complete sorting of the fraction of fair floating ability is arrived at in the course of floating?

Of course, the two fractions are mixed to begin with since the intensity of the outblowing current is not of the critical value that ensures just the floating of the dust particles, but considerably stronger, so strong that it carries off also grains above 0,1 mm size. The sorting is then taking place in the course of floating, and it tends towards an ever greater completeness, as the floating material gradually loses the more coarse grains. However, since coarser grains occur even in the best-sorted dust, the transporting capacity of the air current must be related also to the amount of energy necessary to to carry the coarser grains, as even a single coarser grain can be transported only if the conditions of its lifting and floating are satisfied.

On the basis of MIHÁLTZ's data (14) we can compute the amount of suspended matter deposited in the central area of the town Szeged in 1941.

The total mass amounted to 27 metric tons, in the following distribution:

140 kilograms of medium-grained sand, 0,2—05 mm,

620 kilograms of fine sand, 0,1—0,2 mm,

1,4 metric ton of fine sand, 0,05—0,1 mm,

24,8 metric tons of dust below 0.05 mm.

In all, the amount of the fraction of fair floating ability is a round 25 metric tons, that of the fraction of poor floating ability, 2,2 tons.

Now since the presence of even a single coarser grain indicates the acting of a lifting current of excess power, it is to be assumed with good reason that the fairly floating grains under 0,05 mm are trasnported to the locality where the zone of deposition is developed by a strong wind without or almost without loss. Hence, these grains constitute the unchanging or hardly changing fraction of the suspended group. For this reason, to distinguish these grains from the coarser ones, we call them the basic fraction, whereas the coarser grains are termed accessory fraction. In a strong wind, the grains below 0,05 mm merge almost completely with the transporting medium, and in the powerful current they follow the trajectories of the streaming gas molecules (see *Fig. 9.*).

According to the results of analysis of the dust fallen in this country in the year 1941, also the complete sorting of the suspended dust, resulting in nothing but the basic fraction, is possible. However, this was a special local phenomenon that took place in the area of deposition, after the development of the general conditions of settling, under quieter circumstances. We shall yet return to the discussion of this point.

On considering the process of transport, the presence of the coarser grains suggests that the wind, while it transports, unavoidably creates also the conditions for the scattering of the grains. In the course of this scattering, the grains of higher fall velocity are dropped first. This process is due to the temporary cessation of the lifting force, caused by an involved combination of factors, independently of the changes of the wind velocity. The process can be easily interpreted on the assumption that the entire air mass streaming in the zone of transportation is a disperse system which is unmixed time and again into the gas on the one hand and the aggregate of settling particles on the other. In the disperse state, the lot of the grains forms a mixture with the gas molecules in which no sorting or spatial segregation is at all possible. However, in the state of settling the grains become unmixed and begin to fall, and the grains arriving at the lower boundary of the air mass leave the system for good. It is apparent that it is the coarse grains of high falling velocity which are dropped at the greatest rate off the zone of transportation. However, the rate of decrease is determined among others also by the thickness of the layer of transportation, since the longer the way of settling from the top of the system to the bottom of the same, the more probable is a continued transportation, or, restricting the statement to the simplified case, the possibility of further dispersion.

In summary, the transport and sorting of the grains can take place simultaneously only if the transporting air mass creates conditions in which the gradual dropping off of the coarser grains is possible even without the abating of the current, that is, if the transport is of a double nature.

The sorting that came about in this way does not fit into our general ideas on sorting, according to which the process is solely due to the gradual abating of the transporting force, the slowing-down of the current, that is, essentially to the cessation of transport as related to some grain size category or other. The above process is a consequence of the motion of the transporting medium, that is, of the process of transportation itself, unable to reproduce in all details the conditions of lifting in the course of the periodic rise and fall of the transporting molecules. In a water stream a process of this kind takes place only if the velocity of the transporting current slackens — obviously for some external reason such as a change of the discharge or of the bed of the stream — and the transportation of certain grain fractions ceases as a consequence. This phenomenon is to be considered and termed an external, velocity-dependent sorting. On the other hand, the sorting of the material in eolian suspension is an internal process, a consequence of the nature of the transport, taking place under any current velocity, wherefore it is of a velocity-independent nature.

In all, the transportation in eolian suspensions possesses the paradoxical property of partial lifting inertia, resulting in sorting even if the velocity of the transporting current increases. This phenomenon is a predominant factor of rapid and efficient sorting: nevertheless, it is not expounded in the literature of waste transport in water streams. It is true, though, that its significance is much harder to recognize there. The reason for this is that its influence is manifested only if the transport is taking place along a path of high altitude, when there is no basement (river bed or relief) close at hand from which the repeated sweeping-off of the once dropped particles would be possible.

Here, vertical turbulence seems to be no satisfactory explanation for the mechanism of transportation. Namely, if this condition should prevail, the medium would not only lift but also drop all the grains in a single revolution of a vortex. It is therefore to be assumed that in a given section the number of the grains being lifted is invariably greater than that of the grains being dropped; it is only in this way that the gradual scattering can be interpreted.

Thus, if a vehement gust of wind catches up a lot of unbound sand and carries it off on an ascending path, it drops back in a short time most of the coarse matter even if the wind velocity does not decrease at all. At the same time it keeps on carrying, as a matter of course, numerous coarser grains of exceptional position, even if in a steadily decreasing amount. It follows hence that the development of a well-sorted, fine dust is by no means a necessary consequence of the abatement of the transporting energy. The coarse grains left attest that the transporting capacity of the wind is not at all reduced. The stormy high wind, after it has lost much of its coarse-grained freight without loss of velocity, much like a leaking cart, becomes a mostly unexpolited transporting agent.

In the case of dust depositions of continental scope, the dropping of the coarser grains takes place for the most part in the neighbourhod of the blowout area, whereas the rest is scattered along a path of several hundred kilometres length, resulting in a noticeable deposition of sediment. *(Fig. 26.).* However, the relatively enriched dust content is dropped in more narrowly defined belts or spots, according to observations in those places where the transporting current reaches the border of a different wind system, strikes against the same and is broken up thereby. Hence, in cases like this the deposition of the dust is the consequence of a collision. *(Figs. 19.* and *21.).* In these cases the vertical currents forcing the dust to the ground also play a role not to be unterrated.

It follows further from the outlined interpretation of transport and sorting that the definitions concerning the distance of transportability of grains of a given diameter in a current of a given velocity do not make much sense. Udden has determined the distance to which a single finer and a single coarser grain can be carried by a wind of medium strength. It is a fact that a strong wind may carry a grain of 0,1 mm diameter to distances as much as and even exceeding 500 km, provided the individual trajectory of the particle — the fortunate combination of lifting and horizontal forces — permits. On the other hand, if the conditions are unfavorable, the same grain may become dropped not farther than one kilometre away. Obviously, a wind of medium force is of equal transporting capacity everywhere along is of equal transporting capacity everywhere along its course; in spite of that, it constantly deposits part of the coarser grains, whereas it constantly keeps up the rest. There is no sense in studying the distance of transportability of a single grain; the solution must be looked for in the statistical treatment of the problem, in the consideration of the predominant grain diameter. A wind of greater force drops along a given distance a smaller number of grains, particularly of coarse grains, that is, the material transported to a given target area is of a greater predominant grain size besides being of a greater mass. In a weaker wind the predominant grain size is smaller.

An inquiry into the reason why the grains of silt and clay size are subordinate as related to the coarser grains reveals that this feature is not due any more to the sorting action of the transporting wind. Independently of the distance traveled, the dust will not become finer after having reached a certain limit. It is a general observation that eolian dust and loess contain relatively little material under 0,01 mm grain size, that is, their grain size distribution has a lower limit almost as sharp as the upper one. This circumstance may be retraced to the reason that the eolian dust is the product of redeposition of sediments containing little clay, that is, furnishing few grains of clay size on blowout. The detailed dust deposition study of Miháltz from 1941 (14) which, being based on a series of analyses, also reflects the process of sorting, gives a convincing proof of this statement. The composition of the material deposited in Hungary in 1941, whose grain size became finer from the south to the north, reveals the following: in the dust collected at Miskolc, of 0,01 to 0,02 mm predominant grain size, the abundance of grains under 0,002 mm was 2,68 percent, in the sample from Budapest, of the same predominant grain size, it was 6,69 percent. At the same time there was 7,84 percent of clay in the dust fallen onto the University of Szeged, whose predominant grain size was 0,02—0,05 mm, that is, it contained more finer material than the finer dust samples. This is an irrefutable proof of the fact that the original blownout material contained no floating clay particles, and the very little material of this grain size category was transported adhering to the larger grains. In the opposite case, its amount ought to have increased from south to north in the suspended material, just as the fractions of 0,002 to 0,005 and 0,005 to 0,01 millimetres have increased. However, the abundance of these latter fractions was greater in the Miskolc and Budapest samples than in the material from Szeged; in the case of the 0,002 to 0,005 mm fraction the increase was from 6,4 to 9,7 percent, in that of the fraction of 0,005 to 0,01 mm frcm 7,3 to 21,8 per cent. This shows that the blown-out material contained relatively many independently floating grains of 0,005 to 0,01 mm size and relatively few of 0,002 to 0,005 mm diameter; the latter settled mainly in the last stage, in the north, in the expected sequence of deposition.

The lack of finest grains in the blownout material is explained by the bounded material-producing capacity of air. The presumably most general and most frequent base material of eolian dust is loose wind-blown sand containing little fine-grained mateiral. Hence, the stirring-up of clay particles is impossible to begin with, and in the lack of such no suspension containing clay-size material can possibly develop. Would the materialproducing capacity, the „solvency" of air be as unlimited as that of water, there would be no sharp sorting confined to the 0,01 to 0,05 mm fraction, so well-known in connection with eolian dust and with loess, representing the average of eolian dusts; only the upper limit at 0,05 mm of these sediments would be so sharp, and in the lower ranges there would be a much flatter, much more silt-like grain size distribution curve. The relative abundance of the fraction of 0,01 to 0,05 mm diameter would then decrease from 50—70 percent to 10—20 percent.

In summary, a study of the factors bringing about the sorting of eolian dust leads one to the following conclusions:

The remarkably hight degree of sorting of eolian dust and the predominance of the characteristic grain size of 0,01 to 0,05 mm is the result of three factors: a characteristic property of the resistance of the air molecules, the partial lifting inertia caused by the double nature of the transportation and entailing a rapid and intense internal sorting, and the original grain size distribution of the blown-out material.

However, this explanation is not satisfactory as regards loess, because in this case the sorting must be studied also in the course of the systematic deposition of this sediment. Even the most efficient mechanism of sorting is of no avail if the sedimentation is not continuous and unchanged, or if it is incapable of repetition under indentical circumstances. The loesses of geological importance were formed out of the material of numerous dust depositions, and consequently their sorting and petrographical features can to some extent be considered as averages. The fact itself that the average grain size distribution of loess does not differ significantly from that of the dust deposited in a single event shows that the sedimentation from eolian suspension is capable of being repeated a considerable number of times. This repetition is, however, bound to certain well-defined features, which can by no means be independent of the factors governing the sorting. In repetition, two groups of phenomena are interacting: on the one hand, sorting, which is the expression of the internal motions of the air current and entails the well-defined grain size distribution, and on the other, the repetition of the motion of the medium, resulting necessarily in a transportation at high altitude, dependent on aeronomical factors acting from the outside.

In summary, loess is formed out of suspended material whose grain size distribution has, owing to the nature of the blowout, transport and sorting, an exceptionally high probability of repetition. In other words, this means that the outblowing, transporting and sorting action is of such a nature that it tends to turn any outblown and suspended material into a dust of characteristic grain size distribution.

This interpretation of the genesis of loess has the consequence that the sediments or rocks formed out of eolian dust may be suitable for studies of a general nature, freed of random local influences, on the physics and dynamics of the Earth and of the atmosphere as a whole. This problem was already brought up in connection with the dependence of fall velocity on the force of gravity and the influence of this dependence on the upper grain-size limit of sorting. *(Fig. 6.)* On forming the average grain size distributions of eolian dust deposits and composing a generalized cycle of sedimentation therefrom, it becomes clear after having corrected for the scatter of the grain size distribution that the latter can be interpreted also purely in terms of the density of the medium and the intensity of the gravity field. *(Fig. 11.)*. This fact has a principal significance, in the first place as regards the study of the gravity, Earth density and Earth radius of ancient geological periods. It permits namely to analyze, by studying the grain size distribution of ancient loesses which have presumably

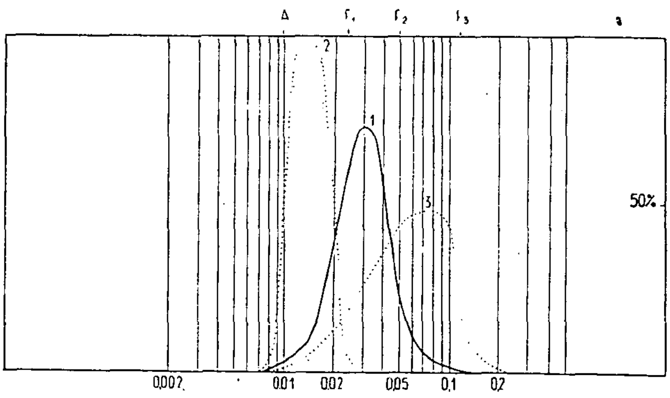

Fig. 11. Interpretation of the grain size distribution of loess *vs.* gravity acceleration.
A: lower limit of sorting
F_1 F_2 F_3: upper limit of sorting
1. Typical loess (according to I. LÁNYI—MIHÁLYI)
2., 3. Typical loess developed under a gravity acceleration ten times as great and ten times as small resp.

formed in the Devonian and Triassic, as well as of other ancient eolian dust deposits, the intensity of the Earth's ancient gravity field, having an important bearing of the problem whether the Earth is expanding or contracting.

The situation is entirely different with fluviatile deposits. These are formed in a medium moving along the surface of the Earth, and they are sorted by a process much influenced by the ever changing local conditions of relief and discharge, that is, by the changes of velocity. Therefore, as the formation of the fluviatile deposits depends on a number of random factors that cannot be distinguished from the general dynamical ones, these deposits do not permit any conclusions of the general nature mentioned above. In the following we shall also consider why this prevails also for sea water, which otherwise is capable of depositing loess-like sediments.

It is beyond doubt that one of the conditions of the poorer sorting of the finer aquatic sediments (silt, mud, clay) as related to the sorting of eolian dust is the wider compass of the material production of water. Another factor is, as stated by STOKES's law, the greater density of the medium, resulting in a narrowing of the chances of sorting of the transported grains. Furthermore, in water there occurs no sudden increase of the drag at a critical velocity, which would permit the intenser separation of some of the grain size fractions. Also, in one of the large groups of streaming-water deposition, in the case of streams, there is not manifested the influence of the above-described partial lifting inertia, since the streaming water can repeatedly pick up the grains dropped onto the bottom of the stream bed or onto the floodplain, provided the velocity of the flow does not decrease. Consequently, in streams even that degree of sorting of the suspended material is impossible which would result from the differences of settling velocities along a path similar to the path of air transport, that is, from a sorting in the „eolian manner". In streaming water, the segregation of the coarser grains from a given aggregate commences only if the velocity of the transporting current slackens, that is, if the state of absolute untransportability sets in for the larger grain size fractions. In this case, the segregated fraction can be ideally sorted, provided the decrease of velocity is slow enough, better even than the fraction which goes on being suspended. Since however in streams and in the flood areas the changes of velocity of the current within a given area of deposition are dependent on the ever changing conditions of water level and bed development, also the grain size distribution of the dropped fraction varies, that is, no uniformly sorted sediment deposited from suspended material can form in this way, at least not in a thick layer and general extension.

The situation is different in sea water, where the currents flow in distinct layers (cold and warm currents, the layering of fresh water flowing in from the continental areas). Here, the influence of the lifting inertia has a free play and it promotes the sorting of the grains within the limits prescribed by the settling velocity. However, for a sediment of complete sorting similar to that of loess (silt) to form, — no matter whether we consider the fraction dropped in the sourse of transport or the fraction which remains suspended but settles later on as a „final product" — it is not less necessary that the state of absolute untransportability should set in, as a result of the slackening of stream velocity, which results in its turn in zonal distribution and continuous sedimentation.

This condition is readily fulfilled in sea water, as the streaming is much more uniform and better-regulated, just like in some correctly operated sludge tank.

The role played by these dynamical factors is decisive even if the role of the reworked loess and of the dust falling directly into the ocean is taken into account as well.

However, just for this reason, silt cannot be the only well-sorted fine sediment in the oceans, whereas in the air every outblown mateiral ends up in the final reckoning in the dust state, owing to the nature of the transport and sorting. That is why dust is of a world-wide extension. In sea water, also other grain assemblages can develop, in dependence of the local stream velocity distribution, that possess a not less excellent sorting.

In summary, we have to mention among the factors of sorting in the general case also the steadiness of the current, which in the case of water may sometimes be of decisive importance.

6. PHENOMENA OF SEDIMENT FORMATION CONNECTED WITH LOESS.

In the foregoing considerations the settling velocity of the grains and the analyses of recent dust deposits were taken into account in the first place. We have sketched the circumstances of dust deposition, the presumable composition of the outflown material, the force of the outblowing wind, the process of internal sorting, the mechanism of transportation and deposition connected therewith. Now let us pass to the analysis of some observations concerning loess. There are known some phenomena of deposition and grain size distribution which merit some attention from the point of view of elucidating the mechanism of formation. A phenomenon of this sort is the horizontal, relief-dependent change of the grain size distribution of loess deposits following the undulations of the relief, as well as some cases of occurrence of sediments transitional between loess and wind-blown sand.

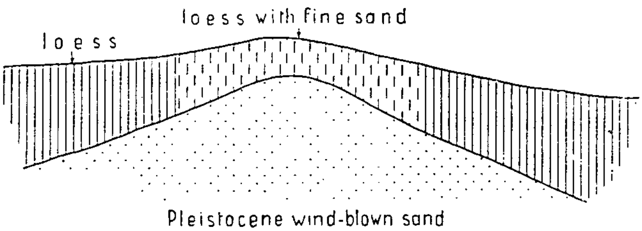

Fig. 12.

The loess deposits of the Great Hungarian Plains mostly overlie an undulous relief, generally that of Pleistocene wind-blown sand, wherefore also the surface of the loess is undulous. In the wave troughs the thickness of the loess is invariably greater, indicating that the loess blanket has to some extent smoothed out the relief differences between the crests and flanks of the dunes. It is an essential feature that in these cases the loess found on top of the crests is of a mostly coarser grain size distribution. *Fig. 12.* represents a loess cover overlying wind-blown sand.

In one of the investigated disclosures of this kind, SW of Kiskundorozsma, by the highroad tofards Kiskunhalas, there is on top of a loess-covered erosional island, in an elevated area of some 3 metres relative altitude a loose loess with fine sand containing dry-land *Gasteropods,* whereas in the deeper-lying parts of the relief there is a more massive, slightly „silty" loess with abundant *Limnaea* and *Planorbis* specimens (*Fig. 13., Fig. 14,* Curves B_1 and A_1, respectively). The disclosure is continuous in a length of some 50 metres. The limit of the drenched and dry-land varieties of loess is blurred. The area was studied in some detail by I. Dobos-Molnár, who drilled a borehole of 10 metres' depth on top of the rise and found mud and clay in a depth of 5 metres.

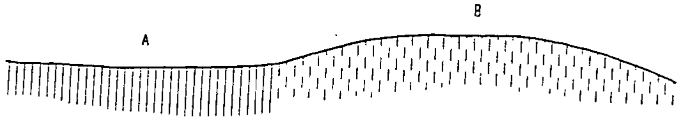

Fig. 13.

Another disclosure is known from beside the road connecting Baja and Csávoly. This loess is purely continental and overlies a deposit of wind-blown sand. The disclosure is 15 metres long and the rise is 2 metres above the nearby hollows. The disclosure encompasses also the underlying wind-blown sand. Samples were collected at two points, at identical distances from the surface of the sand, to exclude the sampling of transitional deposits. Also here the shift of the grain size distribution from the rise towards the hollow is of the same nature as in the foregoing example. (*Fig. 14.*, Curves B_2 and A_2.)

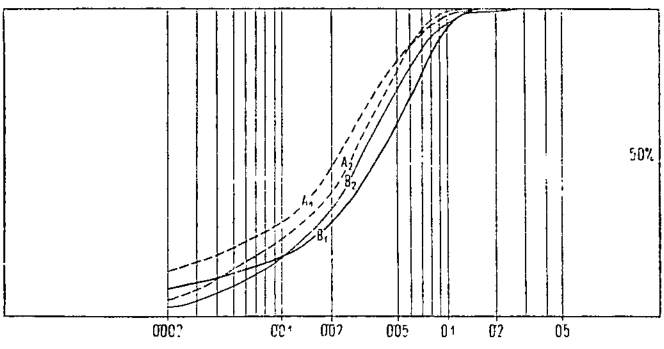

Fig. 14.

This regular variation of the grain size distribution can be explained in the following way: the elevations of the undulous terrain influence the working capacity of the near-surface wind. The rises decrease the cross section of the stream channel and thus increase the velocity of the medium; above the hollows, the converse is true. On the tops there is also some suction.

It is by this near-surface current of variable working capacity that the settling dust is sorted. It is essential to stress that the near-surface air only takes a part in sorting and not in transportation. Namely, in the swifter current the coarser grains, that is, the grains of the accessory fraction, are just able to settle, whereas the finer grains of the basic fraction are swept aside and deposited in the hollows. The dust arriving above the hollows is deposited in its original grain size distribution (basic fraction plus accessory fraction). Consequently, a relative enrichment of the grains of the accessory fraction comes about around the crest, whereas the grains of the basic fraction are actually enriched in the hollow area.

The phenomenon is, as a matter of fact, a natural proof for the existence of the zone of deposition. It cannot be explained except by assuming that the transportation is effected by winds roaming at higher altitudes (zone of transportation) and that there is a quieter air layer more suitable to settling underneath (zone of deposition). Accordingly, the grains arrive from a greater altitude along more or less vertical paths, like snowflakes, and they are arranged as predestined by the relief. Should the transport be effected by a near-surface wind, the coarser grains would accumulate just in the hollows, since they would drop out of the weakening current there before arriving over the next elevation. This process is a peculiar case of the external type of sorting. It is presented by *Fig. 15*.

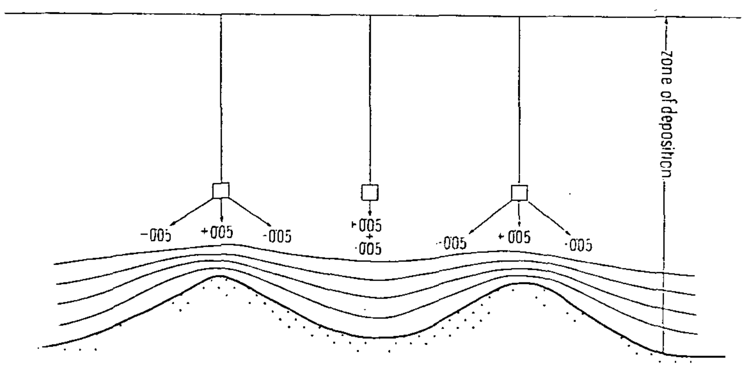

Fig. 15.

The described phenomenon suggests that the dust particles have arrived in the period of loess deposition along near-surface trajectories above the locality of settling, so that the conditions of transport along a path of high altitude do not hold for the process of their sorting. The blowout, which was according to our above results the consequence of a stronger wind, did not take place in the immediate neighbourhood of the area of deposition. The currents circulating here had essentially no transporting capacity and have apported no material, that is, the area was characterized by conditions of deposition.

These circumstances shed light in the first place on the structure of the winds present in the course of dust deposition near the surface, on the lack of any lifting tendency. Thus, for instance, according to Róna (17), in 1901 „the dust falling from higher regions was but thrown to the ground by the lower wind". In his terminology, „lower wind" means the sorting current and the „higher regions" mean the zone of transportation, also distinguishable in the aeronomical sense. Hence, a strong near-ground wind is by no means excluded from the process of dust settling; under such circumstances even the stirring-up of the particles on the ground and phenomena of less regular deposition are possible. The essential point is, however, that these events do not influence signicifantly the striking features of the process of formation; they obscure but slightly the completeness of the horizontal sorting in the investigated area. It can be stated further that in these cases the settling of the dust is final and not just a „rest". The lower wind, even if stormy, is but a concomitant phenomenon of deposition, by no means able to revert its course.

It is here that Udden's (21) observations concerning a deposition of similar nature of eolian dust in present times should be mentioned. Udden studied the material of North American dust depositions taken place in November 1894; January 1895 and February 1896 and he took into account also the circumstances of local arrangement of the deposit. The dust samples originated from an area covered with snow and ice. He found that the dust collected from the middle of the frozen Mississippi canal, far offshore in a plain area, contained fewer coarse grains. On the other hand, in localities where relief forms (riverbanks etc.) or buildings disturbed the current, less fine dust was able to settle.

We have constructed the grain size distribution graphs of five cited samples *(Fig. 16.)*. Samples 146., 150., and 156. were taken in plain areas, whereas samples 152. and 153. came from the riverbanks. The former correspond to the loess of the hollows, the latter to that of the elevations.

Udden has further found that the dust collected on top of the continental ice contained a larger proportion of coorse grains which in his opinion was obviously an admixture off the ground. The case was similar with some samples which were swept on by the wind after deposition and collected for instance in an ice crack. In this respect Udden cites six samples (144., 145., 147., 148., 149., and 151.) whose average grain size distribution we have computed and likewise presented on *Fig. 16.* The analyses were performed by the microscopic procedure but weight percents were calculated.

In connection with the dust deposition of the year 1941, Miháltz (14) also brings up the possibility of mixing with local substances. Close to the sampling locality of one of the Szeged samples there were spots of barren loess and in this sample there was found an unusually high, triple amount of carbonate. In Miháltz's opinion, dust stirred up locally could have become admixed to the dust transported from far away wherever there was a strong wind over dry ground in the neighbourhood of the locality of deposition. This is fairly plausible, for in the sense of the above considerations deposition takes place even if it is hampered by a relatively strong or even stormy near-surface wind, a „dust storm".

Since the accumulation of the dust may thus go hand in hand with mixing with local material, the mechanical and mineralogical constitution of the ground must be attributed a particular importance for the composition of the loess to be formed. This problem was raised by KRIVÁN (10) in the form of the notion of the different origin of loess and loessy sand. In his opision, loessy sand is

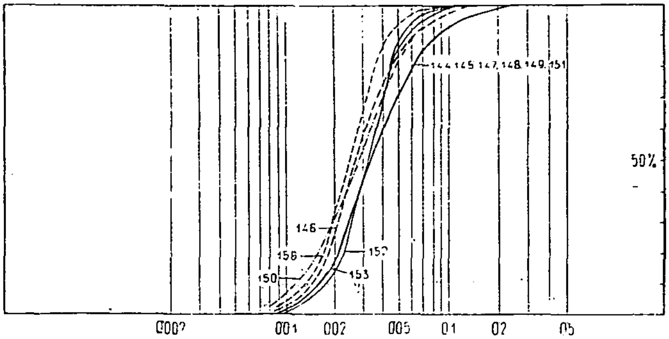

Fig. 16.

actually a mixture of local wind-blown sand and eolian dust from far away. This sediment is found frequently on top of wind-blown sand, merging vertically into loess. KRIVÁN explains the gradual refinement of the grain size by the covering of the free sand surface, by the gradual elimination of the possibility of mixing with sand.

The near-surface currents accompanying the dust depositions in present times warrant the assumption of a mixing of this sort. However, mixing is not less possible between finer and coarser local material and if the grain size distribution of the mixture presents no distinctive features proving the faraway origin of the dust fraction, the formation of the mixture in this way cannot be accepted as proved even if highly probable. Neither does the phenomenon of the evolution of the zone of deposition give any possibility of determining the absolute distance of the blowout locality without a profound study of the circumstances, based on a detailed material analysis.

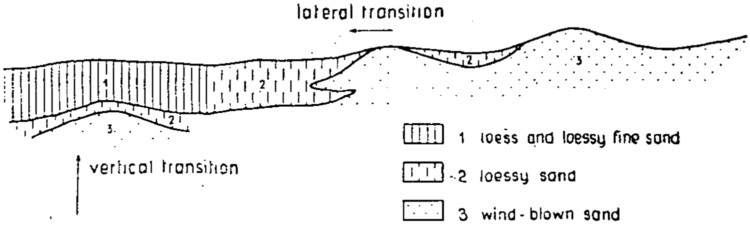

Fig. 17.

The situation is further complicated by the fact that the mixed deposits like loessy sand merge into loess not only in the vertical but also in the horizontal sense, in the manner of lateral facies *(Fig. 17.)*. Our aim in the following will be to study the changes of the grain assemblage from the wind-blown sand towards the loess as well as the nature of the transitional deposits, in order to determine the laws to which the processes of local and mixed (local plus faraway) sediment formation are subject. For this purpose we have developed a technique of calculation serving the numerical expression of the kinship between different kinds of sediment.

7. THE PROBLEMS OF THE RELATION OF LOESS TO WIND-BLOWN SAND. THE NUMERICAL REPRESENTATION OF SEDIMENTARY FACIES.

As regards their grain size distribution, the transitional deposits are intermediate between loess and sand. In this country they occur in a number of localities, some of them in great extension, both above and underground. Their classification is due to MIHÁLTZ (12) and I. LÁNYI—MIHÁLYI (15). These authors distinguish two main groups: loess (0,02 to 0,05 mm diameter) and sand (0,1 to 0,2 mm diameter) on the one hand and transitions between loess and fine sand (0,05 to 0,1 mm diameter) on the other. The aptness of this distinction is proved by the fact that the grain size distribution graphs of loessy sand and sandy loess frequently exhibit two maxima owing to the lack of grains between 0,05 and 0,1 mm. The taller peak may be in the loess just as well as in the sand fraction. On the other hand, loessy fine sand and fine-sandy loess posses invariably single peaks, flatter than that of loess, shifted somewhat towards the grain size domain of fine sand *(Fig. 18.)*.

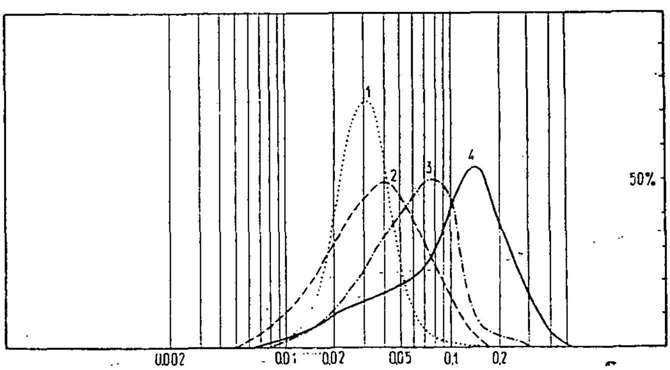

Fig. 18. Loess and transitory deposits according to I. LÁNYI—MIHÁLYI.
1. Typical loess
2. Loess with fine sand
3. Loessy fine sand
4. Two-peak laessy sand

In a summary sense, these formations are systems containing grains of opposed properties, of fair and poor floating ability, respectively. Previously, when we were concerned with a single sequence of sedimentation, we have found that the grains above 0,05 mm float in a strong current just as well as the dust particles do and that they may accompany the latter a long way, while the internal sorting of the suspended grain assemblage leads to the characteristic sequence of evolution, the enrichment of the basic fraction. Although the grain size distribution of the outblown sediment undergoes some necessary changes in the course of suspension, the change is the less, the closer we are to the locality of outblowing. Hence, in the early stages of sorting, especially if the outblown material consisted mostly of sand, there may be formed a mixture containing in a greater abundance grains both above and under 0,05 mm, which under the appropriate circumstances can be deposited in thein entirety. The multiple repetition of the process may lead to the accumulation of huge amounts of sediment. It is essentially this mode of formation that is to be called homogeneous, which means simply that the substance at hand is a sediment that travelled in suspension, a sandy eolian dust.

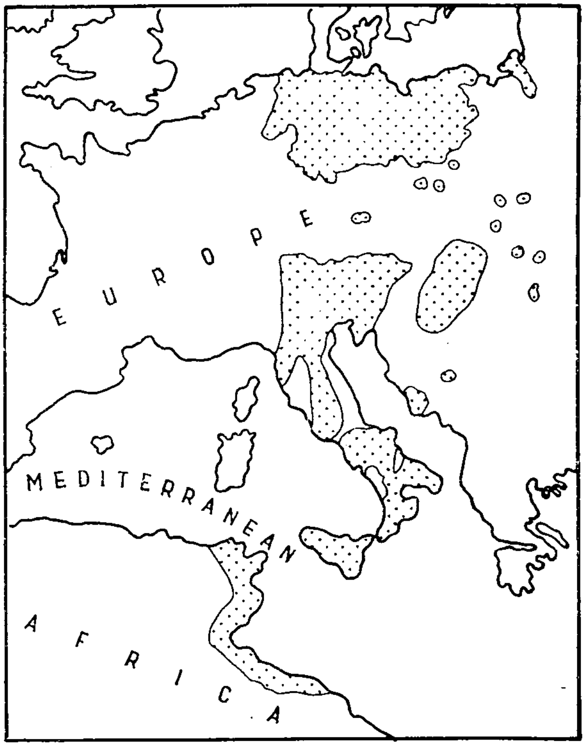

Fig. 19.

On the other hand, the alternation of layers of nearby wind-blown sand and longtransported eolian dust is to be termed a heterogeneous deposit.

The dust deposits of windblown-sand origin of the present times passed in the course of suspension withouth exception through the stage of „sandy" sorting. As far as we know there had been near the locality of outblowing dust depositions of early-stage dust, and it may even be said that this way of formation is an accompanying phenomenon of any dust deposition. However, the outblown material was not deposited in its entirety; on the contrary, it was distributed in several air masses and these fractions underwent a further development as independent systems, which travelled to different distances. The extension of the dust deposition of the year 1901 also shows this phenomenon. *(Fig. 19.,* stippled fields.) The dust deposition of 1941, described above, was essentially also the final stage of evolution of such a separated dustcloud, fallen under the dominancy of the conditions of deposition.

Of course, the breaking-up of the dust cloud and the loss due to deposition of some fragment or other does not contradict the former statement that the grains under 0,05 mm form an unchanging or hardly changing fraction of the suspended material all the way, up to the area of deposition. This remark refers to the sorting taking place in the course of floating and principally in the horizontal section of the path. However, the breakingup and the vertical travel of the dust cloud is a thoroughly different phenomenon involving a change of direction and it is not to be confused with the loss of material taking place in the course of transport. The mode and place of the breaking-up is incidental, whereas the loss of material and the process of evolution are subject to a fixed, uninterrupted schedule.

At a first glance, the concept of the „unchanged fraction" is questionable rather on the grounds that in some instances the 0,01 to 0,02 mm fraction is separated from the swifter-settling fraction of 0,02 to 0,05 mm. This happened e. g. in 1941. The process undoubtedly took place in the course of floating, but certainly in the downward section of the path, after the loss of the accessory grains. A segregation of this kind may take place anywhere in any phase of evolution, in the course of deposition and loss of velocity. The decrease of the velocity of transport does not only rend the individual grain size groups untransportable in the absolute sense, but it also hastens the process of internal sorting.

Our comprehensive *Fig. 20.* presents the sedimentation accompanied by breakup and segregation of the basic fraction in the sense expounded above. The essential point is, consequently, that the segregation within the basic group takes place under the influence, of the conditions of deposition. The radical alteration of the conditions of stream motion leads then necessarily to a general or periodically returning anomalous weakening of the force of the current, that is, it results in wide-amplitude fluctuations of the transporting capacity. While the material approaches the disturbed section of the path, the direction of the current also changes in the vertical sense. The disturbance that takes place can result not only in the loss of the accessory fraction but also in the breakup of the whole system, the segregation of the basic group. The remaining fractions may proceed further to short distances in the original direction, but they are relatively short-lived; the process is irreversible and it soon comes to an irrevocable end.

Observations show that the disturbed zones develop mostly along the line of contact of colliding wind systems (cyclone-anticyclone, 1941, 1942, 1896?). *(Fig. 21.).*

In *Fig. 21.,* the direction of progress of the dust deposition of 1941 and its longitudinal extension was indicated by an arrow. The original direction of the dust mass was a northerly one, but after the carrying cyclone hit an anticyclone, not only the structure and transporting capacity of the wind was changed but also the general direction of progress. In the section between blowout and deposition, no dust falling was observed anywhere, but some very slight deposition of sand is to be mentioned.

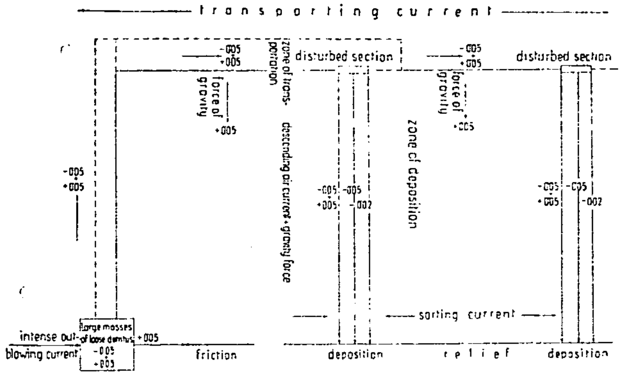

Fig. 20.

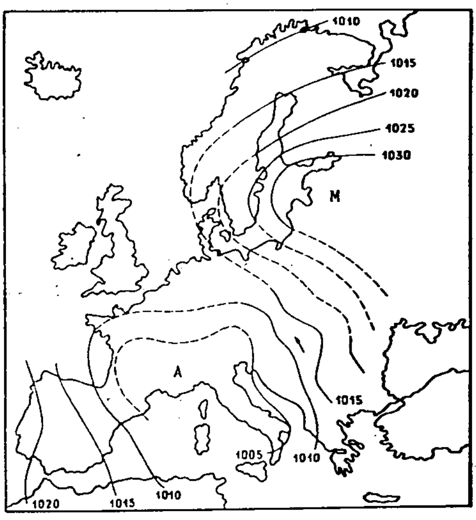

Fig. 21.

Coming back to the study of evolution of the grain assemblages, it shall be our aim to follow the change of composition, the internal sorting of the blown-out material with numerical accuracy from the moment of the blowout up to that of deposition, in order to clear the laws of formation of loessy sand and loessy fine sand, and in a concrete case, to study the problem as to what mode of origin (homogeneous or heterogeneous) is reflected by their constitution and further whether it is possible in the case of a given sediment source to establish kinship from wind-blown sand to loess *(Fig. 17.)*.

We have already mentioned that the turbulent stream carrying the grains has a lifting component in certain phases only, wherefore the lifting frequently alternates with falling in the system consisting of innumerable eddies. This circumstance results in the constant irreversible loss of some grains approaching the bottom of the swirling mass of gas, even without any loss of velocity. From the asemblage of grains, unevenly scattered in the process of transport, the grains of high fall velocity drop out first. However, in the lifting and dropping motion of the turbulent mass of air the process of the drop-out of certain grains occurs at the same probability level as it would in a process of uniform scattering and deposition.

The phenomenon may be illuminated by the following thought experiment. Let us consider a sand containing 10 percent of grains of 0,02 mm diameter, 20 of 0,05 mm diameter, 20 of 0,1 mm and 50 of 0,2 mm diameter, expressed in percents of the total number of grains (e. g. 100 grains). After the total blowout of the sand, the transport is effected by an air layer 50 m thick (zone of transport). This is considered a closed system and within this system we assume a complete mixing of the suspended grains and the air by the appropriate mixing current (state of equilibrium). However, this equilibrium is upset time and again and re-established by the rhythmic weakening and intensification of the current. Thus, the state of complete equilibrium alternates with a contrary state, under the dominance of which part of the grains are secluded from

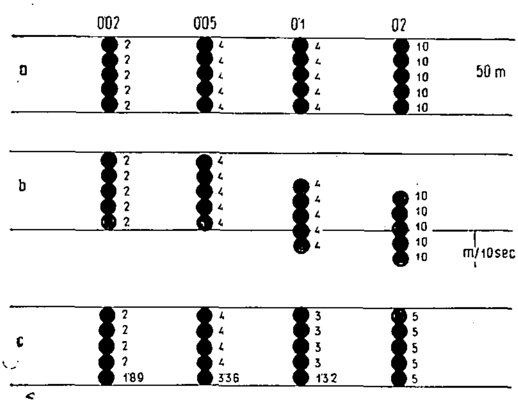

Fig. 22.

the system. This is called the phase of rest („state of no equilibrium"). Its duration is set at 10 seconds and we assume that for this period the air is at complete rest. Namely, the current necessary to keep up the grains of 0,05 mm size hinders, even if slightly, the settling of the grains of the accessory group. This effect influences primarily the smaller grain size classes of that group. However, as we are unable to determine the extent of slowing, we assume periods of complete rest for which we take simply the fall velocities determined in stagnant air.

Fig. 22. shows a complete cycle. The discs represent grains and the number of grains is obtained by multiplying the number of discs with the annexed number. Step „*a*" is the state of equilibrium (complete dispersion), step „*b*" is the ten-second period of rest and step „*c*" the reestablishing of equilibrium.

Owing to the ten seconds' complete rest, 50 percent of the 0,2 mm grains, falling 25 m, and 33,4 per cent of the grains of 0,1 mm, falling 16,7 m in ten seconds, drops out of the system, and settles. Of the grains of 0,05 mm 3,2 percent, of the 0,02 mm grains 1,1 percent is deposited. The reestablished state of equilibrium of step „*c*" finds therefore much less accessory grains and an almost unchanged amount of grains below 0,05 mm, that is, the latter are significantly enriched in the relative sense. The subsequent cycles of similar nature are not shown, but the result as expressed in percents of the total number of grains of the fraction that goes on floating is shown by the table below and by *Fig. 23.* Of course, later on these values must be converted into weight percent.

	0,02	0,05	0,1	0,2	mm diameter
start	10	20	20	50	percent
I. cycle	14,6	28.6	19.7	39.6	
II. cycle	19.6	37,5	17.7	25.0	
III. cycle	24.2	45.4	14.8	15.6	
IV. cycle	27.9	51.3	11.5	9.1	
V. cycle	30.8	55.5	8.6	5.1	

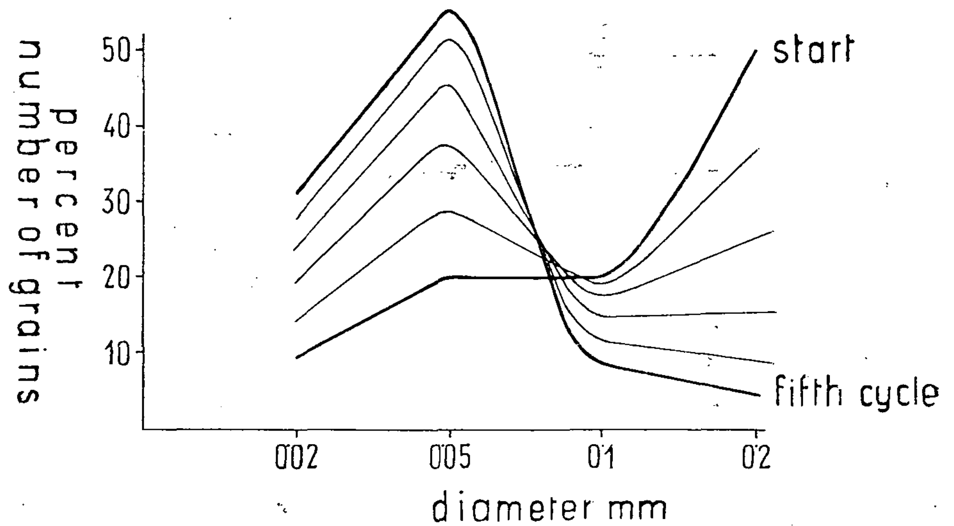

Fig. 23.

For the purpose of computation, we have made the following simple deduction: the thickness of the air layer stands in the same relation to the number of grains in step „*a*" (Sza) as the fall velocity to the number of grains dropping out of the system (Szb) in step „*b*" *(Fig. 24.)*:

$$\frac{V}{Sza} = \frac{e}{Szb}, \text{ whence } Szb = Sza \cdot \frac{e}{v}.$$

Since in the new stage of equilibrium *(„c")* the number of grains is Szc = Sza — Szb,

$$Szc = Sza - Sza \cdot \frac{e}{v}.$$

Within the same set of computations, *e/v* is a constant factor, and thus

$$Szc = Sza - Sza \cdot k.$$

We have deliberated from a number of aspects whether the calculated factors represent correctly the process taking place in nature (14). We shall not go into details here, only give the final conclusion that the described method is suitable to determine the process of evolution of the blown-out detritus and even to play the process back by carrying out the computation in the reverse order, starting from the end product. The computation serves the determination of principially possible compositions, independently of absolute time and space parameters. The reverse computation is suitable to establish the possible ways of development of the grain size distribution. The locality and time at which the individual stages determined by calculation are reached by the actually outblown mateiral depend on the variations of the transporting capacity of the wind.

For the purpose of further computations we have analyzed a desert sand from Libya. We have determined the principal stages of the evolution of the sand aand converted the grain size distribution results into weight percents. The results are summarized in the annexed table.

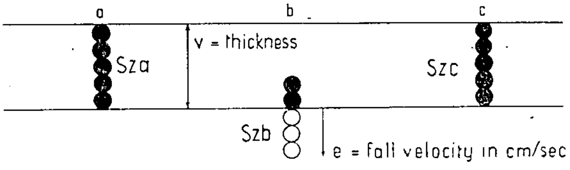

Fig. 24.

Fig. 25. represents the grain-size distribution data obtained by calculation by a set of cumulative curves. It is readily recognized that before the dust fraction is enriched there appears a graph much resembling that of a loessy fine sand. Hence, the peak characterizing the loessy fine sand must necessarily appear in the sorting of natural sands before the development of the dust peak. It is obvious that this material has to be homogeneous, even if it forms a series of considerable thickness; that is, its accumulation does not consist in the superposition of layers of significantly different grain size cistribution (that is, distance of transport). Loessy fine sand is formed out of suspended material which did not yet reach the state of the dust maximum, generally owing to the repeated gusts of a wind of generally identical transporting

Calculated changes of the total weight and grain size distribution of sand transported in suspension under internal sorting, expressed in weight percents.

Cycle	0,01—0,02	0,02—0,05	0,05—0,1	0,1—0,2	0,2—0,3	0,3—0,5	0,5—1,0	1,0—2,0	mm ⌀	Total weight %
Original material	0,122	0,274	8,807	22,905	23,600	12,766	21,190	9,387	weight percent	100,000
1.	0,286	0,636	16,088	30,567	25,687	11,478	13,036	2,223		42,262
2.	0,562	1,231	24,547	34,073	23,353	8,620	6,700	0,446		21,383
3.	1,000	2,164	34,000	34,479	19,274	5,878	3,126	0,080		11,918
4.	1,642	3,514	43,472	32,207	14,683	3,144	1,350	—		7,196
5.	2,495	5,272	51,381	27,811	10,341	2,152	0,532	—		4,699
10.	10,388	20,660	61,089	6,873	1,000	0,739	—	—		1,084
15.	21,650	40,570	36,380	1,564	0,042	—	—	—		0,499
20.	30,900	54,440	14,200	0,060	—	—	—	—		0,336
25.	37,630	62,420	—	—	—	—	—	—		0,265

capacity within a given cycle of sedimentation. This wind may either be a long-range one of greater transporting capacity or a local wind of smaller capacity.

The case is different with loessy sand, or, speaking more exactly, with the two-peak loessy sand. It is clear in the figure that in the course of transport the originally two-peak sand turns into a one-peak one and that no second maximum crops up in the subsequent stages of sorting. This is also a general

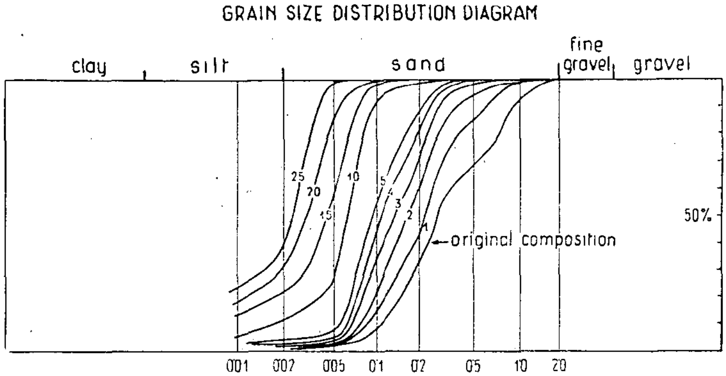

Fig. 25. Process an internal sorting of sand transported in suspension as revealed by the analysis of the eight grain size fractions from 0,01 to 2,0 mm of a sand sample from the Libyan Desert, collected by E. VADÁSZ.

1., 2. Sand stage
3., 4., 5. Stage of loessy sand
10. Stage of loessy fine sand
15., 20., 25. Stage of loess

law of the evolution of grain size distribution: the suspended material has no stage of evolution tending towards a two-peak state. Two peaks can be solely characteristic of outblown material. Sands of this kind cannot be formed except by the mixing of two materials of significantly different grain size, that is, of significantly different distance of transportation and sorting, out of at least two different sediments. In nature, this is realized by the mixture of local, rolled wind-blown sand and suspended dust of long-range transport. This sediment is of a heterogeneous nature. As a consequence, it is not permissible to speak of full sequences of evolution in cases like this, since the dust material is of foreign origin rather than a product of the sediment source of the sand. In this case the dust material of the loess attached to the deposit of transition is also of a more distant origin than the sand fraction. The same is valid for twopeak loess.

The two-peak loessy sand types are especially frequent as vertical transitions, interbeddings between wind-blown sand and loess. Concerning the formations of the horizontal transition we have not yet sufficient evidence, but what is available suggests that here one-peak loessy sand is the more frequent. The composition of this sediment does not exclude the possibility of a homogeneous formation, that is; the deposit is not necessarily heterogeneous, it is not necessary to postulate the mixing of local sand and faraway dust.

To clear the problem in this respect we can make use of another posibility: we must start from the numerical conditions and see whether the loessy sand types of known grain size distribution of the Hungarian Pleistocene could possibly have formed out of wind-blown sand. The problem encompasses an even wider field of facies studies and requires the processing of a huge amount of data. However, there is nothing impossible about its solution, at least in principle.

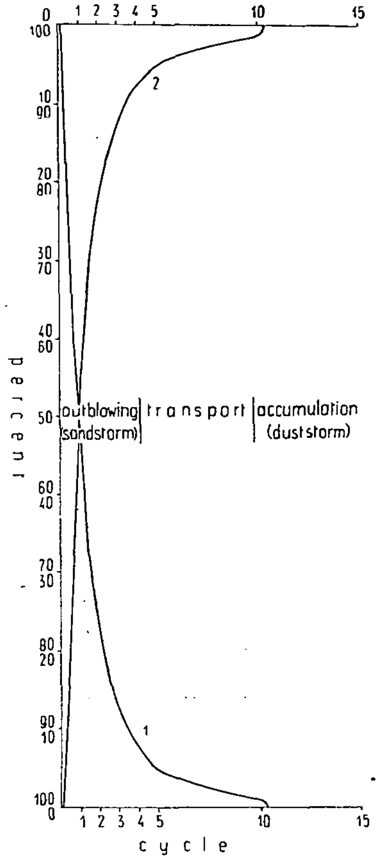

Fig. 26. 1. Amount of transported material in percents of total weight.
2. Amount of settling material in percents of total weight.

Finally, let us present as Fig. 26. for the sake of the quantitative characterization of the internal sorting process the curves of the abundance of the transported and deposited fractions, suitable to define the natural boundaries of the principal stages of sedimentation. The two curves refer to the case of a uniform transporting current and to an accumulation taking place in the tenth cycle of evolution. It is characteristic that the curves have one nearly horizontal section and two nearly vertical ones each. The first vertical section represents the loss of the coarser grains. the horizontal section the transport of the gradually refined grain assemblage, and finally, the second vertical section the deposition of the dust and fine sand. These sections correspond to the stages of blowout, transport and deposition, respectively. In the initial stage there is a sandstorm, in the final stage a duststorm.

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