THE AUSTRALIAN NATIONAL UNIVERSITY

BED-LOAD DEPOSITS OF SHALLOW, UNIDIRECTIONAL CURRENTS

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STATEMENT

In accordance with A.N.U. circular 1139/1962, page 2, paragraph 5, this is to certify that the following thesis represents the sole work of the undersigned except where a reference or acknowledgement is cited in the customary manner.

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Abstract

The techniques of size-shape analysis and sieve analysis were combined in order to study bed load deposits of shallow, unidirectional currents, from both natural and artificial environments, more exhaustively than heretofore. The results follow a very consistent pattern, textural changes, often marked, accompanying changes from one characteristic bed load structure to another as bed particle size, intensity of bed load transportation, or both, increase.

Raised primary structures, such as ripples and dunes, dominate experimental flume beds more than natural beds probably because the stability of these structures depends on temporal maintenance of current direction. Textural characteristics, normally associated with these structures, persist whether the structures are present or replaced by a plane bed. Plane beds are therefore ubiquitous in nature, their presence having little diagnostic value in the assessment of flow conditions. Similarly, current bedding may form in flow conditions other than those characterised by dunes.

Bed load sediments form virtually immediately, from whatever material is available, in response to local hydraulic conditions. Inches or seconds of transportation are all that are required for a sediment with its main textural features developed and characterising the flow

conditions, to form.

Suspended load is, under some conditions, added to bed load deposits in significant quantities. The maximum suspensive power, in terms of grainsize, of past strong currents can evidently be determined from the bed load deposits they have left behind.

Some understanding of the processes involved in bed load sedimentation permits consideration of the significance of river gravels, some effects of depth variation, particle differentiation along the courses of unidirectional currents, the mode of origin of some primary sedimentary structures, the ecological significance of bed load sedimentation, prospects of fossil preservation and the possibility of using some textural features of sands for palaeothermometrical purposes.

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INTRODUCTION

The processes that bring about accretion and removal of stationary particle aggregates in moving fluids are of considerable importance to workers in several disciplines. Inevitably, because of variations in immediate research needs, approaches must vary and be plagued by differing obstacles. Thus an engineer, required to produce a quantitative answer to a problem, may have to lean heavily on empirical methods in order to deal with phenomena he does not fully understand. On the other hand a geologist, a pedologist or a geomorphologist is often confronted simply with a sediment the formative environment of which has left no trace but the sediment itself. Yet again, a theoretician must usually make simplifying assumptions in order to proceed but the more numerous the simplifications the less applicable are the results in natural physical environments.

Because a complete understanding of sedimentation would obviously solve the problems of all concerned with the involved phenomena, it is inevitable that the research efforts of all must be convergent in their basic intentions. Almost as inevitably, perhaps due to lack of coordination and communication between workers in different disciplines, some fields within the general framework of the problems repeatedly receive major attention whereas other fields, often left isolated between disciplines, receive little attention or even none at all. Flume studies directed towards furthering the understanding of bed load movement and deposition are common; so are exhaustive granulometric studies directed towards ascertaining the relationships of sediments to the physical environments in which they form. Obviously work combining the two fields would be very interesting but such work is practically non-existent.

Differentiation of bed load particles into sediments and the formation of primary sedimentary structures such as ripples and dunes give geologists hope of distinguishing between fossil environments. The same processes represent an unwanted complexity to those seeking a satisfactory bed load function. Many more complexities exist. For example, we can observe that bed load sediments are typically laminated on rather a fine scale, each lamina coarser or finer than the ones above or below it, and separated from them by sharp junctions. If one recognises these facts one must also accept that, in almost all natural environments, bed roughness due to particles must be always changing, often suddenly. Moreover, it also seems inevitable that, because of the specialised composition of the laminae and the sharp junctions between them, it is extremely unlikely that the bed load and a lamina forming from it would ever have the same composition, save by chance; and if the lamina and the bed load have different compositions then it follows that the composition of the moving bed load grains must be forever changing. Although we can hopefully assume that these differentiations may "average out" over a large area of the bed, one dare not disregard them when considering the formation of an individual sediment sample which must usually be characteristic of a very small area of the bed and a short period of time. At the present time it is doubtful if the problems involved when turbulent water moves an assortment of irregular particles can be listed, leave alone solved.

Against this somewhat complex background the present project was designed to increase understanding of the actual mechanisms involved in the formation of bed load sediments in shallow unidirectional currents - a topic which, rather surprisingly in view of its position at the hub of many problems, has received comparatively little attention. Basically, the study involves concurrent consideration of the relevant properties of the particles - size, shape and specific gravity - and the physical properties of water in a gravitational field over a surface essentially inpenetrable to water and particles. At a more practical level the work necessitates a somewhat exhaustive study of the textural and structural properties of bed load sediments together with assessment of the hydraulic conditions under which they form. It should be noted that the mental separation of "textures" and "structures", often to be studied separately, although long established, seems to be purely arbitrary and possibly perfidious. Undoubtedly the two collections of phenomena are intimately interconnected in many ways.

Before proceeding with a description of the main project it is necessary, firstly, to review some of the more pertinent literature and, secondly to describe certain preliminary investigations which were conducted in order to integrate the techniques used, to assess their reliability, to set up certain standards for comparative purposes and, more generally, to enhance the chances of success of the main investigation.

Forms of granulometric analysis are of some antiquity (Krumbein 1932). Folk (1966) has recently given an extensive review of the subject. The technique involves taking a sample from some natural or artificial environment and studying the results of some measure of the size distribution of the sample. The first pertinent question to ask seems to be "What, precisely, does a sample represent?" If one is interested in the physical processes of sedimentation and one knows that bed load sediments are, almost always, laid in turbulent water with ever changing flow characteristics and that the sediments themselves are usually intimately laminated, the only sensible sample, theoretically, would be an infinitely small one from within an individual lamina. The practical answer must therefore be to take a sample as small as will give reliable results with the techniques used from within an individual lamina. Although Udden (1914), who published the first paper on granulometric analysis that was of sufficient scope and quality to achieve wide recognition, thought in an analogous manner, to this day comparatively little attention has been given to the physical meaning of samples. It follows from the above reasoning, in a completely unarguable manner, that a sample that includes material from two or more laminae does not represent an act of sedimentation at all; in fact such a sample represents nothing that ever happened in nature and would only be of any use as a sample if one were trying to sell the sand. Very large samples, ideally a whole beach or the entire contents of a trench across a river valley, may be of interest for some purposes after random splitting to laboratory size. But between the "point sample" and the huge bulk sample, as far as the study of sedimentation is concerned, all samples must be almost useless.

Although it must have been obvious to earlier workers that successive bed load laminae differed in mechanical composition (see, for instance, Thompson, 1937) it was not until 1938 that papers by both Apfel and Otto were published advocating sampling from individual laminae. As recently as 1964 Ehrlich pointed out the need, once more, to sample from individual laminae and exemplified the associated scientific advantages. Emery and Stevenson (1950) sampled from laminae as did Walger (1961). More recently such sampling has become more commonplace. The author (Moss 1962, 1963) subjected small samples from individual laminae to size-shape analysis and, probably largely due to the sampling technique and the consistency of natural sedimentation, obtained results that were, in turn, extremely consistent environmentally. Basumallick (1966) made size analyses of a series of successive foreset laminae in Rhine alluvium and Hand (1967) subjected such samples to individual settling velocity analysis.

Friedman (1961, 1966, 1967) described his sampling method and it appears that most, or all, of his samples must have come from individual laminae. Unfortunately, in many papers on granulometric analysis, the type of sample used is not recorded and so the accompanying quantitative results are of doubtful physical interest.

Sieving and settling tubes are both used extensively in granulometric analysis. Some workers advocate one, some the other (Folk, 1966). It seems axiomatic that, were an association of particles selected naturally in terms of size then sieving would be the best method; if in terms of settling velocity, then the settling tube would be best. Unfortunately natural sediments are too complex for the choice to be made with confidence.

Approaches to the handling of the data produced by granulometric analysis are highly varied. Udden (1914) made little attempt to handle his data mathematically but tended to interpret them in terms of physical observation. Later, many workers used more mathematically elegant approaches but tended to neglect the physical side of interpretation except, perhaps, as afterthoughts. Because the processes are physical such approaches must be regarded as largely empirical. Workers have tended to split into two main groups in their methods of analysis. One group tends to regard a size distribution as continuous, at least for the purposes of calculation, and to work out, on this basis, such conventional arbitrarily defined parameters as mean size, sorting skewness and kurtosis. The physical meaning of these quantities is often obscure and probably variable. Attempts are made to differentiate environments, usually by drawing scatter plots of one parameter against another and some degree of success has been achieved particularly between air-laid sands, sea beach and river sands. Among many papers are those of Mason and Folk (1958), Friedman (1961) and Chappell (1967). No major attempt appears to have been made to differentiate between the deposits formed under varying unidirectional currents, that is, in terms of velocity, depth and other parameters. A recent study by Friedman (1967) is important in that major attention is paid to the physical processes of sedimentation and the differentiation achieved is based on samples not subject to geographical restriction. Friedman's field separations in the plots are good but not at a level that would permit the technique to be applied reliably to a single sample.

The second major group assumes that a size distribution is actually a combination of two or more physical populations and attempts are made to separate them. Such an approach requires the assumption that some distribution law applies to at least one of the admixed distributions. Fuller (1961) and Walger (1961) used such an approach. Dissection of a size distribution seems difficult to justify unless in the face of some ancillary evidence.

Most workers who study the shape of particles have been more interested in such topics as change of shape with distance of transportation than in any direct effects that physical environments may have on the selection of particles with respect to shape. Hagerman (1936) was the first worker to consider shape in the latter manner. Later the author (Moss 1962, 1963) used size-shape analysis in modern and ancient environments. Because of the large size of this study there is room to repeat only a few of the more relevant conclusions here. The work showed that ordinary bed load sediments were indeed complex in nature and that subaqueous current-laid sands consisted of combinations of three particle populations. These, named A, B and C were distinguishable by their size-shape characteristics. In any one sediment A made the main framework, B was fine and interstitial to A, and C consisted of particles larger than those of A. Beach sands consisted, usually, of A alone but current-laid sands always contained both A and B. C was sporadic in occurrence but became the dominant constituent of current-laid gravels; otherwise A was always dominant. A approximates log-normality in size distribution and its presence has probably been the major stimulus to workers who attempt to resolve size distributions into components. There was, however, no evidence that either B or C had log-normal size distributions. Because A is always present the major environmental variations are due to B and C. A makes the main framework of the bed (save in current-laid gravels) but B consists of particles small enough to pass into the interstices of the A grains. Clearly the presence or absence of B must affect conventional statistics, particularly skewness, and it is of interest that nearly all discriminations between river and beach sands depend on there being more "fine tail" in the former. Unfortunately C, which consists of grains coarse enough to roll over the bed surface (made by A) and whose presence seems to depend largely on immediate availability of suitable particles, "pulls" the statistics (particularly skewness) in the opposite direction from the "pull" due to B. In size analysis, therefore, C can partially balance the effect of B on statistics and may well be responsible for some of the failures to achieve environmental distinction by size analysis. The existence of resemblances between the results of size-shape analysis and size analysis was well demonstrated by Friedman (1967). Such resemblances have immediate practical significance. Whereas size-shape analysis seems to give a much clearer picture of the physical make-up of sediments with respect to dynamic populations, size analysis gives a much better result for the size distribution. Clearly the two techniques are complementary. Therefore, in the present study both are used simultaneously.

Perhaps the major use of primary sedimentary structures by earth scientists, to date, has been in the empirical determination of stratigraphic sequence and palaeocurrent directions. It is being increasingly appreciated, however, that some such structures exist over only limited ranges of physical conditions and, consequently, must ultimately be very useful in the unravelling of the nature of environments existing when fossil sediments were formed. Sorby (1908) noted the existence of a sequence of primary bed load structures with increasing current strength and Owens (1908) noted the sudden disappearance of ripples and the onset of rapid transportation of bed load over a plane bed as a current became stronger with time. Sequences of structures with increasing bed load transportation rate were produced by Gilbert (1914) in his classic flume studies. But only since the appearance of the work of Simons and Richardson (1961) and Simons, Richardson and Albertson (1961) has major attention been paid to the potential usefulness of such structures in the interpretation of environments. Using a medium sand mixture (average grainsize 0.45 mm) in a large flume these workers established a detailed sequence of bed forms with increasing transporting power. For tranquil flow regime the sequence was :- plane bed without movement, ripples, dunes and a transitional stage from dunes to rapid flow forms. For rapid flow regime the sequence continued:- plane bed with movement, standing sand waves and antidunes. It was observed that a similar sequence could often be descried in natural flows. This sequence is not necessarily universal; coarse sands, for instance, do not show the ripple stage. But it does give general guidance as to the structural sequence that can occur in shallow unidirectional flows. A series of papers by Allen (1963a, 1963b, 1965) have brought together a large amount of work on these sedimentary structures (particularly ripples and dunes). He has also classified their variations, largely geometrically. In the present work this now well established series of primary structures has been used as a general guide to flow conditions both in the field and in the laboratory.

Many quantitative studies of bed load transportation have been made and the approaches to this difficult problem are almost as numerous. Leliavsky (1955) reviewed much of the earlier work. Approaches may be almost purely empirical (Lacey, 1958) or partially empirical and partially based on theory (Einstein 1950). Rubey (1938) reviewed the three major mechanisms by which a current of water can exert forces on a particle resting on a stream bed. Basically these are due to friction, impact and fluid-dynamic lift. Most approaches assume that one of these is relatively so important that the other two can be neglected. Usually the underlying theory of an approach assumes that the important motive forces are either frictional (drag) or due to impact. Fluid dynamic lift is very difficult to quantify for practical application, although Jeffries (1929) evaluated it for simple cases. Several workers, however, consider it to be important (Einstein 1950, Leliavsky 1955). Shields (1936) related the ratio of the force exerted by flowing water to the resistance offered to it by a layer of sand grains to the ratio of the grainsize to the thickness of the associated laminar sublayer. One ratio was found to be a universal function of the other. This important relationship has been utilised by many later workers.

In recent years it has become increasingly recognised that there are really two sorts of bed load sedimentation, distinguishable in terms of concentration of moving particles just above the bed. In the ripple stage the free flow is in contact with the bed and bed load grain motion is essentially individual, each grain following its own path. Intergranular collisions above the bed are rare. In the dune stage, although bed load particle movement is more intense, the situation is essentially similar. However, as bed load transportation intensifies, intergranular collisions above the bed eventually become inevitable and the bed load forms a rheologic mass or "traction carpet" moving between the bed and the free flow. Thus bed load grains, so to speak, form a physical environment of their own, driven by the current from above and retarded by the static bed below. This type of motion takes place over the plane bed, standing sand wave and antidune structures. Grains deposited on, or removed from, the bed must pass from, or into, the rheologic mass. Bagnold (1954, 1955, 1956, 1966) has made an extensive study of this type of bed load motion. He has demonstrated the existence of a dispersive pressure within the mass, caused by intergranular collisions. He has also been able to predict the conditions for the onset of this type of bed load motion. The physical conditions prevailing during the two types of bed load motion are, in fact, so different that, in future, they will probably require separate quantitative treatment. One of the aims of the present work was to learn to distinguish between sediments formed under the two types of bed load motion.

Most bed load sedimentation takes place in turbulent water but quantitative approaches must usually be based on temporally averaged conditions. Also conditions must usually be averaged over the bed area of the artificial or natural channels. Kalinske (1941) has shown that local velocity fluctuations near the bed may reach two or three times the average velocity and it is when temperal velocity maxima occur that grain motion is most likely. In fact, just above the threshold conditions for bed load movement, the motion of individual grains is probably entirely dependent on such local velocity maxima. It has already been concluded that, if one is interested in sedimentation, the only sensible way to sample a bed load sediment is to take as small a quantity as feasible from within an individual lamina. Because most natural bed areas are built of laminae of different composition, hydraulic parameters averaged over both time and area cannot be applied to an individual small sample. The flow conditions half-way down a dune foreset, for example, bear little relationship to the averaged flow conditions over the bed. Thus, in terms of averaged hydraulic conditions,we could only hope to predict a range of associated sediment types that could form but not the nature of some individual sediment at a point on the bed. An "average sediment" compounded from small samples from points on the bed surface would, unfortunately and for reasons already discussed, be not very useful.

Application of existing hydraulic studies to natural sedimentation is further restricted by the fact that much experimentation utilises particle assemblages of much smaller size ranges than are usually encountered where unidirectional flows occur in nature. Also, the frequent use of sediment-recirculating flumes places yet another restriction simply because, if any sorting processes take place on the bed, the rejected grains are promptly returned to the upstream end of the bed and, presumably, the more unsuitable a grain is for acceptance into bed sediments the more often will it be presented to the bed. In nature such a grain would simply be passed on downstream. There is little mention of particle differentiation in flumes in the literature. An exception is Straub (1935) who reported differentiation down a flume in material about 4 mm. in diameter. He recorded a fall in particle size downstream but also stated that the reverse grading could occur. Einstein (1950) also described size differentiation.

It is to be hoped that, ultimately, it will be possible to reconstruct the nature of depositional environments from the evidence left in fossil sediments. The first systematic attempt to tackle such a problem has already been made by Jopling (1966) who used the structural and textural properties of a fossil set of foresets and associated bottomsets as a basis for computing hydraulic parameters. A number of assumptions had, of course, to be made and it is not possible to judge how nearly correct were his quantitative conclusions because, as yet, no suitable yardstick exists.

The current project was planned so that approximately equal amounts of information would be derived from natural and artificial environments. After describing the preliminary investigations, two major sections will be devoted to the sediments formed in natural and artificial environments. Next, a section will derive conclusions from both. Lastly, some applications of the results will be described and discussed.

The figures to which reference is made in the main text, together with appendices, are presented in an accompanying volume.

TECHNIQUES AND PRELIMINARY INVESTIGATIONS

This section involves describing the two main techniques used - size-shape analysis and sieving, steps taken to integrate their usage, the establishment of certain standards based on suites of grains of similar volume and settling velocity, the comparison of these standards with some natural particle assemblages and an empirical study of sieving designed to assess the general usefulness of sieve data.

Size-shape analysis was described by the author (Moss, 1962). Briefly, it involves measuring three linear dimensions of a particle corresponding, approximately, to length, breadth and thickness, as rapidly as possible. In order to rationalise results a more-or-less rigid definition of the three dimensions is followed and the dimensions have been given special names in order to avoid confusion. Quoting from Moss (1962, p.341):-

> "The size dimensions of particles are therefore considered in terms of a "long dimension" (p), a "medium dimension" (q), and a "vertical dimension" (r), approximating, respectively, length, breadth and thickness.
>
> "The three dimensions of particles longer than approximately 5 mm. are measured with calipers; smaller particles are measured with a microscope that is fitted with an eyepiece micrometer and a graduated fine-focusing

> adjustment. Sand samples to be measured are placed in a flat-bottomed glass dish, the floor of which has been roughened with very fine abrasive. When a microscope is in use and only p and q are required, solely for measuring purposes, each particle is assumed to be laminar. The position of the point that would then be its center of gravity is estimated and the longest and shortest distances across the grain and measured through this point are taken as p and q respectively. These two measurements are not therefore made at a measured right angle to each other although they are nearly so for most particles. The avoidance of angular measurements makes the technique relatively rapid."

The vertical dimension (r) is somewhat tedious to measure and was held in reserve for use in special cases in the present investigation. Moss (1962) continues:-

> "If a sample has a large range of particle size, a number of sets of measurements covering successive ranges of p are taken, using suitable objectives for each range and, if necessary, calipers."

In the present investigation, if some part of a size range was of particular interest, extra data were collected over this range, as desired. Also, it was found that p and q could readily be measured on a projection head fitted to the microscope at about twice the working rate previously achieved and with much less eyestrain. The head used projected the microscope field onto an area about 10 cm. in diameter and grain images were measured with a 5 cm. ruler to which a small handle had been fitted in order to facilitate rapid manipulation. Using this method, a thousand grains per day can readily be measured.

> Still quoting from Moss (1962, p.350):-
>
> "For general exploratory purposes only p and q have been measured and use has been made of a simple shape function defined thus:
>
> $$\text{Elongation Function} = \frac{p}{q} = \frac{\text{long dimension}}{\text{medium dimension}}$$
>
> "This is plotted against p" ... "Because the number of particles measured is usually large, full individual treatment of these data would be very time-consuming. Instead" ... "the mean elongation function is found for successive equal numbers of particles with respect to p, and curves, hereinafter called 'elongation function curves', are fitted to the resulting mean values. If the true elongation function curve is linear, this method of curve fitting is accurate, but if gradient changes occur the curve obtained deviates from the true

> curve. However, the amount of deviation can be kept small if the range of p covered by the particles used for each mean elongation function value is small compared with the range of p over which significant gradient changes occur."

In the present study, distributions of the elongation function, over small ranges of p, have also been used. Figure 1 illustrates the method of measuring grains and the preparation of an elongation function curve. Also shown is the method used for coding measurements directly, values of q being written down against corresponding values of p. This method saves much time.

Because of their frequently complex nature, most elongation function curves are fitted by eye. There is actually overwhelming evidence that these curves manifest one set of physical phenomena over some part of their length, another set in another part and so on. Consequently an equation fitted to them would have little physical meaning. Appendix 3 deals with this matter and also shows individual point scatters for sediments and artificial particle suites.

Accurate size measurement is difficult to achieve, at a satisfactory working rate, for irregular, small particles. Strictly, volume is the only true measure of size. Because most bed load sediments are dominated by quartz particles and others of similar specific gravity the weights of enough individual particles would give a reasonably accurate picture of the size distribution. Automation would be necessary to achieve a satisfactory working rate. In the absence of this the choice was between sieving and settling velocity measurement. Sieving was chosen because, although it does not give a true size separation (shape is also involved), it is less susceptible to differing errors from true size measurement with absolute size than are settling velocity methods. Another advantage of using sieving is that it is a standard technique the use of which here helps to connect the present study with the results of more conventional work.

Settling velocity, or parameters closely related to it, are quite likely to be important in some possible processes involved in bed load sedimentation. For example, if fluid-dynamic lift is of importance in raising particles from the bed, the actual force required to lift an individual particle may well bear a fairly consistent relationship to the settling velocities of the particles. For this reason it was thought desirable to obtain elongation function curves for sets of particles having essentially constant settling velocity. Unfortunately, interaction between particles and fluid varies with absolute particle size or, more precisely, with the Reynolds Number. Therefore it was necessary to prepare a series of curves for particle suites covering almost the entire conventional sand size range.

The settling velocities were determined by dropping grains, for which p and q had already been determined, individually into a tall glass jar of distilled water held in a thermostatic bath at 25°C ± $\frac{1}{2}$°C and timing their descents through 28.5 cm. The glass jar was 20 cm. in internal diameter so that side effects on settling velocity would be negligible. Because a large shape range was advantageous a mixture of many sands, ancient and modern, nascent and mature, together with disaggregated weathered granite, was used as a source for the experimental grains. Quartz grains only were picked from the mixture in order to avoid specific gravity variations.

The range of settling velocities actually used in the plot was 0.68 to 10.69 cm./sec. The data were grouped into successive fractions each having a settling velocity range covered by a factor of 1.10. An elongation function curve was prepared for each fraction. The average number of grains per fraction was approximately three hundred. Figure 2 shows the elongation function curve for the 0.74 - 0.82 cm./sec. fraction with the 95% confidence limits drawn for each point which, in turn, represents a mean elongation function value for twenty grains. There can, of course, be no reasonable doubt that the elongation function curve is very close to being linear and that it has a strong positive gradient.
Of course, it is to be expected that such a suite would consist of relatively small, equant grains associated with relatively large, inequant grains but the immediate question, for present

purposes, is whether or not the curve is actually linear.

Figure 3 shows all 29 such curves for the entire measured settling velocity range. The relationship apparently remains linear throughout the investigated range, the gradient of the curves merely falling with increasing settling velocity. These curves were also destined for empirical use as standards of reference for sorting measures. In view of this, and because it seems reasonable to suppose that a natural selection of particles with respect to a single parameter, such as settling velocity, would not always approach perfection, Gaussian distributions with increasing size ranges were also prepared from the data. The distributions and the resulting elongation function curves are shown in Figure 4. Within the range investigated the elongation function curves apparently remain linear for Gaussian distributions but the gradient falls as the spread of the distribution increases. Clearly, however, if the range of the distribution became sufficiently large the elongation function curves would not remain linear for the central part of the curve would eventually represent all grains in the original mixture over a large range of settling velocity and would consequently inherit the form of the elongation function curve for the parent mixture. It would, of course, be possible to select a suite of quartz grains with unusual shape properties and with the same settling velocity that did not have a linear elongation function curve. It does seem likely that natural quartz grains have an overall consistency in shape properties due to the consistent mode of origin of the vast majority of them (Moss, 1966).

It appeared just as logical to investigate the size-shape relationships of a suite of particles of the same size (i.e.volume) as to study a suite with the same settling velocity. This is an easier task because there is less need to cover a large size range in the investigations. Two suites of quartz particles were individually weighed. The first consisted of 400 rounded vein quartz pebbles all weighing between 3.000 and 3.552 gm. Spheres of the same volume would have diameters in the range 12.92 - 13.68 mm. - a range covered by a factor of 1.06 as against 1.19 for a "quarter-phi" sieve fraction. The second suite consisted of 125 coarse quartz sand grains whose volumes were equivalent to those of quartz spheres in the size range 1.41 - 1.68 mm. - equivalent to one "quarter-phi" sieve fraction.

Figure 5 shows the elongation function curves of the two preparations of nearly constant size. (The full scatter for the quartz pebble data, together with those for a suite of grains of nearly constant settling velocity, are given in Appendix 3). The 400 quartz pebbles are divided into 20 sets of 20 pebbles and the 95% confidence limits for each such point are plotted. There can be little doubt that the curve is non-linear, the gradient increasing with p. Furthermore, the 125 coarse sand grains give a curve of apparently similar form though, of course, of lower reliability.

That a contrast should exist between the form of the elongation function curves of a suite of grains of constant settling velocity and one constant volume does seem reasonable (given that specific gravity is constant). One cannot say precisely why the former curve is linear or very nearly so but, at least over the range investigated, it apparently is so. Given this, it can be reasoned that, whereas the settling velocity suite must consist of an association ranging from small equant grains to considerably larger inequant ones, if derived from the same parent suite of particles, a constant volume suite must range from small, equant grains to equally small inequant ones. As length increases then the product of breadth and depth must decrease. One would therefore expect the elongation function curve of the constant volume suite to start climbing much more quickly than that of the constant settling as p climbs to higher values.

Considerable further interest attends this apparent contrast. Figure 6a shows the elongation function curves of three intertidal, wave-laid beach sands collected from the same beach at the same time (locality:- Perranporth, Cornwall, England). These curves, and many others like them from similar environments but different localities were obtained by the author (Moss 1962). Superimposed on the natural sand curves are three of the nearly constant settling velocity curves for material of about the same grain size. In two cases the natural sands approach the artificial proparations in steepness (No. 56; 2.98 as against 4.44 mm^{-1}: No. 60; 2.48 as against 3.47 mm^{-1}) and their curves are evidently linear.

Figures 6b and c show the elongation function curves for wind-laid sands. Two of them (Nos 366 and 75), published by Moss (1962), were from coastal dunes and the other, No. 748, was from a desert dune. This is not the only type of curve yielded by wind-laid sands but is apparently rather characteristic of sands built into raised structures. That these curves resemble the nearly constant volume curves is beyond dispute. It is also of interest that No. 75 is from the same locality as the three beach sands (Nos 53, 56 and 60).

The physical significance of these comparisons will be considered later in the thesis. The theme was not further pursued because of other evidence given later in the thesis. Time has, as yet, not permitted the preparation of more standard grain associations with respect to single parameters. All forms of granulometric analysis must be used comparatively and the usefulness of such standards must surely be potentially great. A similar approach was used by the author (Moss, 1966) when investigating the mode of origin of quartz sand grains.

Ownership of two suites of particles of almost constant size gave an opportunity to investigate the nature of sieving in a practical manner. Most investigations of sieving have been largely theoretical (Sahu, 1964, 1965). The sand grain suite was sieved for fifteen minutes on a sieve shaker in 8 inch, square-holed sieves. The pebbles were hand sieved through square-holed sieves but every pebble was pushed through the meshes as far down the sieve bank as it would go, trying it in different attitudes until it either passed a sieve or, almost certainly, could not pass the sieve without breakage of either mesh or pebble. Thus, the sieving of this suite must have very closely approached technical perfection.

Figure 7 shows sieve analyses of the two preparations. Their cumulative curves are compared with their known true size ranges had the particles been spheres. All cumulative curves in this thesis are presented as in this figure, with the smallest particles on the left. This is the reverse of the convention followed by most sedimentologists but facilitates simultaneous thought on size and size-shape data. All 400 pebbles passed the 15.94 mm sieve but only 76 came to rest in the 12.63 mm sieve which would have retained all had they been spheres. The bulk of the pebbles (257) lodged on the 11.08 mm sieve, 66 were retained on the 9.50 mm sieve and one passed through to the 7.92 mm sieve. In short, the sieves could only show that, in terms of sieve diameter, the pebbles were covered by a factor of two. If sieving is assumed to give a size measure the results imply that the pebble volumes were covered by a factor of eight as against the true volume range of 1.19.

It was, of course, readily apparent qualitatively that the sieves really made a shape separation of the pebbles.

The mean elongation function for grains on 16.63 mm sieve was 1.26, those on the 11.08 sieve averaged 1.42 (close to the overall average of 1.44), those on the 9.50 mm sieve averaged 1.76 and the single grain on the 7.92 sieve had an elongation function value of 2.78.

The flatness function (Moss, 1966) is given by:-

$$\frac{p + q}{2r}$$

Its average value for the same sieve fractions, in descending order of sieve size was 2.05, 1.72, 1.80 and 1.89 for the single grain on the finest sieve. That is, the flatness fell then rose again.

Actually the particles distributed themselves in a rather complex way as follows:-

Flattened grains have their sieve size controlled by their breadths and the "coarsest" grains of a given true size come to rest on a sieve provided that their breadths exceed $\sqrt{2}$ times the sieve diameter. Next to come to rest (as sieve size decreases) are rather equant grains that are approximately tetrahedral in shape. These are closely followed by nearly spherical grains (It will be recalled that the flatness function fell to its lowest value in the second sieve fraction in the current experiment). Next come the normally shaped grains approximately fairly equant biaxial ellipsoids in shape. These are followed by more elongated particles and finally, by very elongated ones whose breadths and depths are approximately equal. It is clear that the sieve size range of particles of the same size depends on the shape range and, more particularly on whether or not extremely flattened or extremely elongated grains are present. Such grains are more likely to be broken into more equant grains in natural environments than are grains that are equant already (Moss, 1966). The quartz pebbles used did not have a particularly large shape range and the results suggest that, in some materials such as marine sands rich in shell fragments or very labile sands derived from metamorphic terrains, particles the same size could, possibly, be distributed through as many as six "quarter-phi" sieves.

The sieving results given by the 125 sand grains were so similar to those given by the pebbles that they need not be detailed. It is of interest that equivalent spheres would have all passed a 1.680 mm sieve and come to rest on a 1.410 mm sieve - that is, they would be equivalent to a "quarter-phi" fraction. In fact, all the grains passed the 1.680 mm sieve, 63 (mean elongation function 1.44) came to rest on the 1.410 mm sieve, 54 (mean elongation function 1.61) came to rest on the 1.190 sieve and 8 (mean elongation function 2.28) passed through onto the 1.000 mm sieve. The shape range of coarse quartz sand grains is characteristically low (Moss, 1966).

Figure 8 shows elongation function curves for two successive "quarter-phi" sieve fractions from a natural river sand. The curves are steep and evidently linear. Again the stronginfluence of shape on sieve fractionation is shown.

Superimposed on the plot are two curves for sets of grains of nearly constant settling velocity. The latter are very much less steep. It seems highly probable, therefore, that a set of grains of constant settling velocity would be split into several sieve fractions.

Figure 9 shows the result of weighing 50 quartz grains from each of three successive "quarter-phi" sieve fractions and converting the weights to volumes. In the figure the volume ranges for equivalent spheres is also indicated. As can be seen, overlap in true size between successive fractions is considerable, the volume range of one sieve overlapping that of the next sieve but one. Of the 150 grains 65 were larger than the largest possible sphere that could enter their sieve fractions, 84 fell within the volume range covered by spheres that could be present in their sieve fractions and only one was smaller than the smallest possible sphere that could exist in the sieve fraction.

This small, practical investigation of sieving makes the magnitude of shape effects on the technique evident whereas they seem to have been appreciated only qualitatively up to the present. Sieving can be regarded as a form of size analysis only if shape does not vary. The shape variations occurring in natural particle assemblages are sufficient to affect results considerably. Sieve analysis can be conceived as approximating a size analysis for large size distributions but, as the size range of the materials being studied becomes smaller, sieve analysis gradually becomes a complex form of shape analysis. Between these extremes sieving is a sort of size-shape analysis. Any one sieve fraction will range from flattened grains through more normally shaped grains to elongated grains up to several times the size of the flattened grains, according to the shape characteristics of the material being sieved. Similarly, grains of the same size can be distributed through, probably, three to six sieves. Because of such effects any sudden changes of gradient in a true size distribution curve will be blurred in sieve analyses because the effect will usually be recorded gradually over a series of sieves. Bimodality could become apparent unimodality. The extreme ends of sieve distributions must be highly shape sensitive - the fine end is often off sieve range but the coarse end is not. Typically the coarsest sieve fraction of a sand consists of flattened particles and it is often enriched in mica flakes or flattened quartz grains, metamorphic rock fragments or shell fragments. The present data are insufficient to confirm suspicions that sieve intervals as small as "quarter-phi" may not be justifiable in usage. Certainly there would seem to be little point in using more closely-spaced intervals. Also, it appears highly likely that, for natural size distributions as narrow as those of aeolian dune sands and sea beach sands, sieve results must be measuring shape as much as size and that, hence, recent successes in the differentiation between such materials by sieve analysis must depend just as much on shape differences as on size differences. Clearly, care should be taken, and perhaps some allowance made, when sieving statistics of mature and nascent materials are compared. There is a great need for a reliable form of size analysis. Possibly round-holed sieves would give better results than square-holed sieves.

Finally three curves were prepared for general empirical use. Figure 10 relates sieve size to medium dimension (q) thereby providing a link between sieving and measurement. Figure 11a relates the gradient of the elongation function curves of the suites of grains nearly perfectly selected with respect to settling velocity at 25°C to the settling velocity of the grains. Figure 11b relates the same gradient values to the long dimension value of the curves at an elongation function value of 1.55 - a likely mean elongation function value of Population A's in the present investigation. This plot enables the gradient of Population A in the elongation function curves of complex sediments to be compared with the gradients of the elongation function curves of particle suites almost perfectly sorted with respect to settling velocity.

RESULTS FOR NATURAL SEDIMENTS

Introduction

The method of attack used on natural sediments was to collect single-lamina samples of modern bed load sediments the dynamic environment of formation of which could be observed or reliably inferred. Such samples were then subjected to both size-shape analysis and sieve analysis and attention was paid to any environmentally persistent features of the results.

Rivers provide the most readily accessible deposits of shallow unidirectional currents and all but a few of the samples used were river deposits. Rivers also give the advantage of providing obvious evidence of the source of the particles being investigated. Because it was desired to make the study approach, as nearly as possible, the general case with respect to bed load sedimentation, rivers deriving their materials from areas of dominantly granitic terrain were considered most suitable. Because most of the rivers within a hundred miles of Canberra derive the bulk of their detritus directly from weathering granites, their aureoles and mildly metamorphosed fine grained Palaeozoic sediments, most of the samples were taken from this area. The Murrumbidgee and its tributaries were extensively sampled. However, for comparative purposes, a small number of samples was taken from the tidal estuary at Narooma, N.S.W.

In situ weathering, often deep, has affected the local granites to the extent that relatively few granite pebbles occur in the local rivers. Most coarse particles consist of metamorphosed fine arenites, quartz porphyries, vein quartz and a variety of locally important materials. These rivers are supplied with a continuous size range of material ranging upwards to at least 50 mm. and sometimes to over 500 mm. in diameter. Feldspar is surprisingly uncommon and most of the sand-sized material is completely dominated by granitic quartz grains with rather flattened metamorphic rock fragments as the most important minor constituent. Mica (mainly biotite) is an interesting minor constituent. Some of it is not present as thin flakes but as fairly equant pseudohexagonal crystals.

Three major criteria were used for recognising the stage of bed load sedimentation under which sampled sediments formed. The first was the actual presence of primary structures (Simons, Richardson and Albertson, 1961) - ripples and dunes (or megaripples). Samples taken from some part of a recognisable primary bed load structure obviously form in the stages characterised by them. The second method involved the presence and absence of pebbles for, in the ripple and dune stages, pebbles of 30 mm. in diameter or larger cannot be moved a significant distance horizontally (Fahnestock and Haushild, 1962). Thus the presence of pebbles within a sandy deposit, either liberally scattered individually or as gravel segregations, makes it virtually certain that an intimately associated sandy deposit would have been laid by a rheologic bed load mass, driven by a strong current. (The term "rheologic bed load" is used here as a more sedimentologically suitable term than the "upper regime" of Simons, Richardson and Albertson (1961). The term is used to describe bed load moving as a dense mass over the bed.) Some environments were still active when sampled and some experience was gained in observing the intensity of particle motion associated with the different stages. After a while this came to be the third method for recognising the stage of bed load sedimentation.

In the well known flume studies of Simons, Richardson and Albertson (1961) a plane bed was hardly attained at all during the entire series of runs. It occupied some part of the bed after the onset of their upper regime. In nature, both in ancient and modern environments, a plane bed is the most common bed form. It was soon recognised during sampling trips that raised primary sedimentary structures <u>can</u> occur over certain ranges of conditions but a plane bed is a common bed form too, not confined to any one set of flow conditions. Not only this, but current bedding, not readily distinguishable from that made by dunes, occurs in both the ripple stage and in strong flows capable of moving large pebbles. Typically such current bedding occurs in regions of convective deceleration - delta-like situations. These structures were studied in a flume by Jopling (1964).

It was observed, during collecting trips, that ripples formed of fine sand were apparently smaller, flatter and firmer than ripples composed of coarser sands.

Figure 12 is a sketch of an active sampled area from Deep Creek which discharges into Lake George, twenty miles north-east of Canberra. A small delta capped by ripples was advancing over an area also covered by ripples at a point where an anabranch rejoined the main stream. Between the two trains of ripples atop the structure was a region with an essentially planar level bed. Study of particle motion in this active environment left no reasonable doubt that the whole bed load motion was in the ripple stage, yet planar bedding occurred as well as foresets some eight or nine inches high. This case is, of course, clear cut but there were other examples in the field that did not allow ready diagnosis of depositional conditions. In such cases, sampling was avoided. Standing sand waves and antidunes were not encountered in the field so their physical environments could not be knowingly sampled. The general impression was that, in the ripple stage, plane beds were just as common as rippled beds, the two occurring together often with ripple trains dispersed here and there over an otherwise plane bed. Coarse sand has no ripple stage but coarse sand beds showed patches of dunes in otherwise plane beds. For rheologic stage deposits the plane bed was dominant. Locally caused current bedding apparently occurred in all recognisable flow stages and was common immediately downstream of gravel banks, the presence of which evidently stimulated its formation. Jopling (1964, 1965) caused this to develop under differing flow conditions in flume experiments.

Major differences between flumes and natural flows arise from the presence of vertical flume walls. Apart from offering general resistance to the flow, these walls hold the current straighter than would be the case in nature. Cross-current turbulence components must be damped and larger temporal variations in current direction at any point in the bed must be almost eliminated. On reaches of the Naas River it was noticed that a coarse sand (too coarse to make ripples) exhibited dunes on the sharp bends of the river but the bed was planar on the reaches between the bends. Ripple trains often occur close to banks but fade away towards mid-stream. (Examples, including some reversed ripples are shown in Figure 12). Ripples and dunes are, of course, orientated structures with respect to current direction. The general evidence from flumes and streams suggests the hypothesis that the stability of ripples and dunes is related to temporal persistence of current direction and that features such as flume walls and river banks, by holding the current direction comparatively invariant with time, create an environment that favours the formation of such structures. Similarly on a sharp river bend the flow is directed by the banks and is less subject to temporal variation of direction than is the flow on straight reaches between the bends.

Ripples formed on the upstream slopes of dunes were encountered only twice during the investigation, once in the Murrumbidgee and once in the estuary at Narooma. In both cases the dunes were in very shallow water so that the actual ripple crests were within about two inches of the surface. These ripples appeared to be more symmetrical than normal current ripples.

Some of the samples collected were very small. They ranged from 0.2 gm. for fine sands up to more than a kilogram for gravels. All were allowed to dry and elongation function curves were prepared for them before any form of grain separation took place. Later they were sieved using four inch diameter sieves for the sands and eight inch diameter sieves for the gravels. It was found that very small samples were easier to sieve than more conventional (50 gm. or so) samples. Very little material became lodged in the sieves and that which did could be quickly removed. All natural sediments investigated are described in Appendix 1.

Ripple Stage Sediments

Figures 13 and 14 give the elongation function curves for three natural ripple stage sands. The 95% confidence limits for each mean elongation function point are plotted. (Calculating these limits is very time-consuming so they have been worked out for a few sediments only. Having done this, other elongation function curves of similar form and based on similar numbers of data are assumed to be equally reliable - see Appendix 3). No. 1107 is a Type 2 sediment (Moss, 1962) lacking Population C. The other two (Nos. 1184 and 1188) are Type 3 sediments, having Population C. Figures 15 and 16 show the elongation function curves for twenty-six ripple stage sands derived from ripple foresets, level bedded areas and larger scale foresets of the ripple stage. The four graphs have different horizontal scales, the sands actually varying from very fine to coarse. In spite of this the curves show a consistency that is remarkable. To initial inspection they vary in only two ways. Firstly, Population C (responsible for a levelling out of the curve towards the highest long dimension values) may be present or absent (present in 13 samples, absent in 13). Secondly, the other (fine) end of the curve stops abruptly (because of a lack of material to measure), usually still in the sand range, for the coarser sands; but for the finer sands the fine tail usually continues into the argillaceous size range. The fine tail is due to Population B.

Population C consists of particles larger than their neighbours and these relatively large particles would probably be capable of rolling over the Population A grains which must make the main bed surface. It was expected, therefore, that Population C would be less likely to be present on foresets than on level areas. In fact, however, no relationship was discerned between the distribution of Population C and the form of the bed surface. In the field it was observed that, whereas the grains making the bulk of ripple sediments move in low-trajectory saltation, making short jumps up to a few diameters above the bed, a few somewhat larger grains can often be discerned rolling over the bed surface. The motion of grains small enough to make Population B (the fine tail) was not observed in nature. The effect of turbulence on the bed in the ripple stage is readily observable. One can concentrate attention on a few square centimetres of bed and observe almost no grain motion for a minute or so. Then, suddenly, ten, twenty or even more grains will be set in motion in the area. After a second or two, comparative quiescence will return. Significant transportation of grains along ripple troughs, across the direction of the main current, was sometimes observed.

The samples were subjected to sieve analysis and the results were plotted on semi-logarithmic paper. Arbitrarily, at the coarse end of the distribution, after the number of grains per sieve fraction fell below twenty, a curve of best fit was drawn. If over twenty grains occurred per fraction the curve was drawn through all points. Figures 17 and 18 give the cumulative curves for all the natural ripple stage samples. All the coarser ones are very alike. Bearing in mind the limitations of sieve analysis when considered as a size analysis and the small size range of these sediments, it can be observed that each has a long, straight portion accounting for most of the sediment. All have short coarse tails but the sieving study has made it evident that almost all particle assemblages must show such a feature, particularly if they contain tabular particles. (It was qualitatively obvious that flattened grains, particularly micas, were often concentrated in the coarse sieve fractions of these sediments). At the fine end of the distribution of the coarser ripple sands the short, abruptly ending tails are probably more significant. Some of them contain virtually no material of sieve size less than 0.25 mm. This is, of course, very interesting in view of the composition of the material being fed to the streams. There must, almost certainly, be a hydraulic explanation for the phenomenon.

The finer ripple sands (50 percentile less than about 0.25 mm.) have cumulative curves slightly less regular than do the coarser ones. The fine tails are different too, some containing significant proportions of argillaceous matter.

Because the evidence of the existence of Populations A, B and C seems incontravertible, it seemed wise to attempt to split the sieve analyses into parts, each representative as nearly as possible, of a single particle population. The author (Moss, 1962) achieved separation of size-shape data by the use of q-curves. These involve the time-consuming measurement of the vertical dimension (r). This procedure was followed in a number of cases and the actual result was, in each case, the same as would be achieved if the data were split on the assumption that the linear portion of an elongation function curve, attributable to Population A, continued in a linear manner into the overlap zones with Populations B and C. By removing grains with successively larger values of the medium dimension from the fine end of the original data it is possible to arrive at a splitting value which leaves the Population A curve continuing freely and in a linear manner into the finer p ranges. Similarly, successively smaller values of the medium dimension are removed from the coarse end of the data spread until a splitting value is obtained that enables the Population A curve to continue in a linear manner through its previous region of overlap with Population C. Having separated out Population A, the remaining data (not used to plot the curve for Population A) are used to construct curves for Populations B and C. Figure 19 shows the data for No. 1188, the original curve of which is shown in Figure 14, split into three component curves.

The splitting of the size-shape data allows the splitting of sieve data by reference to Figure 10. The two splitting values are merely converted to sieve diameter. Separate sieve cumulative curves can then be drawn for each population and values for the percentage of each population in the sediment can also be obtained.

Figures 20 and 21 give the resulting sieve cumulative curves for the Population A's of the ripple stage sands.

Mostly they are almost straight lines between the 20 and 80 percentiles. The coarsest (Nos. 1175 and 1146) are exceptions. The "tails" are largely technological. If Population C is present the coarse tail sieving effect affects this Population; if Population C is absent then Population A must be affected. Thus a separated Population A shows no coarse tail if Population C is plentiful, a small coarse tail if Population C is sparse and a well developed coarse tail if Population C is absent. The same sieving effect affects the fine tails to a lesser extent for Population B, albeit sometimes in small quantities, is always present.

An important feature of the curves is that they give a value for the 50 percentile of Population A. Because Population A, in most bed load deposits, is responsible for the bed grain roughness, this figure is of value. The curves make it obvious that the size range of ripple stage Population A's is very small. What variations they show will be discussed in a later section.

Figure 22 gives the separated Population B cumulative curves for the ripple stage sands. The point previously made concerning two types of Population B in these sediments according to grains size can now be expressed more precisely. If the 50 percentile of Population A is over 0.25 mm. (see Figures 15 and 16) then, in the local rivers, ripple stage sands do not contain measurable quantities of silt and clay in Population B. In fact the Population B's consist, almost solely, of particles only a little smaller than the smallest associated Population A grains. If, however, in the same flows, the 50 percentile of Population A is less than 0.25 mm. then, quite suddenly, silt and clay become acceptable to these sediments in significant quantities. Further consideration will be given to this seemingly significant difference later. (It will be recalled that it was noticed, in the field, that ripples made of fine sand differed in form from those made of coarse sand.)

Figure 23 shows the separated Population C curves for the ripple stage sands. Accepting that the coarse tails are, at least partially, due to the nature of sieving, this Population consists, in every case, of a concentration of particles only slightly coarser than those of the associated Population A's.

Population A was quite dominant in the ripple stage sands, averaging 87.4% and ranging from a lowest value of 63.6% up to over 99% in some cases. Population B was variable, ranging from 0.3% to 28.2% and averaging 7.1%. All of the higher Population B values belonged to sediments whose Population A 50 percentiles were less than 0.25 mm. In fact the coarse ripple sands averaged only 2.8% Population B against 16.7% for the fine ones. Population C was absent in half the ripple stage sands. Its average proportion, if present, was 5.5%.

The coarsest ripple stage sand in an actual ripple had a Population A fifty-percentile of 0.756 mm. (No. 1175). A coarser sand, No. 1146 with a Population A fifty-percentile of 0.915 mm. occurred near the base of a foreset in the current bedded structure shown in Figure 12. Coarser ripple stage sands than these could not be found.

Dune Stage Sediments

Dune (or megaripple) stage sands were treated in exactly the same manner as were ripple stage sands. Figure 24 shows the elongation function curves of two dune stage sands plotted in detail. No. 1223 is a river sand and No. 1245 is from an estuary. Figures 25 and 26 show the curves for twenty-one other dune stage sands. These curves are very like those of the ripple stage sands and, save when a dune stage sand is coarser than the coarsest known ripple sands, distinction between individual samples from the two stages has not been reliably achieved. The only general difference appeared to be that both coarse and fine tails of the elongation function curves, due to Populations C and B respectively, were more variable for dune stage sands than for ripple stage sands.

Figures 27 and 28 show the sieve separation results for the entire dune stage sediments. Again, they are very like the results for the coarser ripple stage sands. The gradients of the central portions of the curves are, perhaps, more variable so that curves cross each other more often and, usually, the fine tail is better developed. No dune stage sand contained measurable silt or clay.

Figures 29 and 30 are cumulative curves for separated Population A's. They show the same tail phenomena, largely dependent on the abundance of Populations B and C as do the ripple stage Population A cumulative curves. No dune sand could be found in the rivers with a Population A 50 percentile less than 0.30 mm. The estuarine sands, however, had Population A 50 percentiles of just over 0.25 mm. The coarsest dune stage Population A 50 percentile was over 2.1 mm. and there is no evidence suggesting that even coarser ones do not exist. The evidence, in fact, suggests that whereas ripple stage sands run from finer than the sand-silt junction to just under 1.0 mm. in terms of this parameter, the dune stage seems to be absent in fine sands but apparently persists to over 2.0 mm. in coarseness. That is, the two stages have different but overlapping size ranges. Results published by Guy, Simons and Richardson (1966) and by Williams (1967) also strongly suggest that very coarse sands do not form ripples.

Figs. 31 and 32 give the separated Population B cumulative curves for dune stage sands. They show the same concentration of particles just smaller than the associated Population A particles but, as was evident from the entire sediment curves, for the rivers, the fine tail is more pronounced. Fig. 33 gives the dune stage Population C cumulative curves. These are, again, very like those of the ripple stage. They show a concentration of grains just larger than the associated Population A grains and have very small size ranges. This result seems rather remarkable for one would expect that, for the same Population A size, a current strong enough to cause dunes to form would have more ability to roll large particles than would a current capable only of building the material into ripples.

Population A averaged 83.3% in dune stage sands as against 87.4% in ripple stage sands; Population B was 7.1% in each case; Population C was more abundant (when present) averaging 9.4% in the dune stage as against 5.5% in the ripple stage. These comparisons are somewhat weighted because the dune stage figures include four estuarine sands which were very poor in both Populations B and C. Also no dune stage equivalent of fine ripple stage sands was found. A more rational comparison of the two stages must result from using river sands from the overlapping size range only. The comparison (with ripple stage figures first) is as follows:-

Population A 91.9% as against 81.8%
Population B 2.9% as against 8.9%
Population C 5.3% as against 8.3%

These figures suggest that Population A is not quite as dominant in the dune stage as it is in the coarse ripple stage.

The results for both the coarser ripple and the dune sands suggest that a vertical force associated with the bed-flow interface must exist and be capable of repelling grains, only a few times smaller than the Population A grains, almost completely and thus keep them from entering the bed. Cases were seen where this rejected fine material seemed to return to the bed downstream of patches of coarse ripple sand and to build fine ripple sands there. Whatever the nature of these forces, they are at maximum effectiveness over beds of medium sand in the ripple stage. These forces appear to be slightly less strong (or less reliable temporally) in the dune stage. The effect of these forces diminishes dramatically in the ripple stage if the Population A fifty-percentile falls below 0.25 mm. Fine and coarse ripple stage sands differ, in fact, more than coarse ripple and dune stage sands. This topic will receive further attention later in the thesis.

Rheologic Bed Load Sediments

Rheologic stage sediments created numerous difficulties during the investigation. Firstly, sediments in this stage usually form only under strong flows and cannot usually be seen forming in rivers nor can they be sampled from individual laminae while still forming. This is because, almost invariably, suspended load concentrations make the bed invisible. Secondly, the great size range of many of these deposits and their complex nature required the collection of a very large number of data for each sample so that only a limited number of samples could be investigated. In some cases over 6,000 measurements had to be made on a single sediment before reasonable confidence in the detailed shape of the elongation function curve could be established. Because the local rivers, when flowing strongly, habitually mix, in the same depositional environment, sands and gravels in intimate association the two types of deposit were studied simultaneously.

A much greater change in bed load behaviour occurs between the dune stage and the rheologic bed load stage than occurs between the ripple stage and the dune stage. It was therefore hoped that the present investigation would reveal distinctive textural characteristics of rheologic bed load deposits. Moss (1962, 1963) noted that, for some sediments, a sharp maximum appeared to occur in the elongation function curve apparently in that part of the curve influenced by both Population A and Population B. It was suspected that this feature would, in a more detailed study, reveal itself as a characteristic of rheologic bed load deposits. Figure 34, the elongation function curve of No. 1180, a level-bedded river gravel of generally conventional appearance in the field, shows that these hopes were well founded. The curve is shown on two scales, an enlargement of its fine end showing various features that occur below a long dimension value of 5 mm. and the whole curve, ranging up to

50 mm. 6.300 measurements were taken in order to fix the shape of the curve with satisfactory accuracy. The 95% confidence limits are given for each elongation function mean.

(To anyone who is familiar only with simple relationships between variables Figure 34 must seem odd or even outrageous. It must be remembered that an elongation function curve represents the relationship of a purely arbitrary shape measure to a purely arbitrary size measure. A whole host of physical influences on the sediments can manifest themselves by affecting such a relationship in one way or another. The curve is, in fact, analogous to a seismographic record but it moves with length (grain size) instead of time. Just as a seismologist picks out the influence of different physical phenomena on his record, so is it necessary for an elongation function curve to be assessed in terms of different physical influences being important over different size ranges. Violent "bumps" in elongation function curves usually represent the waning of one physical influence and the incoming of another.)

Considerable effort was devoted to these sediments because the major features of this curve repeat themselves in other curves over different ranges of the long dimension and must therefore be manifestations of dynamic processes. Moreover these processes are the depositional processes of the rheologic bed load which is extremely difficult to study directly. The interpretation of the curves was tentative at first, pending confirmatory evidence from other sources.

Detailing the features of the elongation function curve of No. 1180 from the lowest values of the long dimension (p), firstly the curve falls steeply from the start of the measured range to a sharp minimum at p = 0.45 mm., $\frac{p}{q} = 1.51$. The curve then climbs steeply to p = 0.7 mm., $\frac{p}{q} = 1.63$; next occurs a more gentle minimum at p = 1.4 mm., $\frac{p}{q} = 1.57$. The curve then rises evenly to a maximum at p = 2.4 mm., $\frac{p}{q} = 1.67$. Next a rather remarkable feature occurs in that there is a sudden drop to p = 2.7, $\frac{p}{q} = 1.61$. A linear rise then persists to a maximum at p = 4.1, $\frac{p}{q} = 1.71$. After that the curve falls to another minimum at p = 7.0, $\frac{p}{q} = 1.55$. Above this size the number of data obtainable was less due to the relatively small numbers of pebbles, as compared with finer particles, in a sandy gravel. However, the curve appears to climb to a maximum at about p = 35.0 mm., $\frac{p}{q} = 1.67$ then to fall to lower elongation function values once more for the highest values of the long dimension.

To avoid further tedious description it is necessary to name some of the recurrent features of the elongation function curves of rheologic stage bed load sediments. These are defined with reference to No. 1180 (Figure 34):-

Feature 1

This feature is exemplified by the minimum at

$p = 0.45$ mm., $\frac{p}{q} = 1.51$ in the curve. It is qualitatively obvious, when making the measurements, that this feature always corresponds with a marked diminution of particle abundance with falling particle size. This coincidence of properties makes the feature virtually unmistakable.

Feature 2

This feature is exemplified by the asymmetrical maximum shown in the curve at $p = 2.4$ mm., $\frac{p}{q} = 1.67$. The author (Moss, 1962) published curves with features resembling this one (see, particularly, Figures 5 and 15 of that paper). Resolution of these curves by the use of q-curves showed the feature to belong to the overlap zone between Populations A and B. A noteworthy example was No. 475, a river sand from Arran, Scotland, shown in Figures 5, 9 and 12 of that paper. This feature was ascribed, in the main, to a concentration of elongated grains in the coarser fractions of Population B (Moss, 1962, 1963).

Feature 3

This is taken as being exemplified by the maximum at $p = 1.41$ mm., $\frac{p}{q} = 1.71$. If the initial interpretation of feature 2 is correct then feature 3 must be the overlap of Populations A and C. Similar features were shown to be due to this overlap by Moss (1962).

Figure 35 represents a river sand, No. 1232. The curve apparently shows features 1, 2 and 3 as does No. 1180 but, of course, the sample contained no pebbles. The contrast between this curve and those of ripple and dune sands of similar coarseness leaves no doubt that it can be distinguished from them. Also, there can be little doubt that a rather profound change in the mechanism of sedimentation takes place with the onset of rheologic bed load transportation.

Figure 36 shows the curve for another gravel, No. 1228. Feature 2 is very well marked and what appears to be feature 1 is evidently very close to feature 2. Figure 37 shows three sands. The first (No. 1235) was from a current bedded foreset in a deposit downstream of a gravel bank. Its curve shows features 1 and 2 but lacks feature 3 because Population C is absent. No. 1236, closely associated with No. 1235 but level bedded, shows all three features (it has Population C). Comparing Nos. 1235 and 1236, it will be noted that, in spite of close association in the field (they were within two feet of each other and evidently products of the same flood), features 1 and 2 do not occur at corresponding values of the long dimension. This is strong further evidence that these features must be considered in terms of fluid dynamic processes, not in terms of provenance. No. 1230 appears to have its feature 2 very suppressed or even absent.

Figure 38 shows the curve for No. 1160, another gravel apparently showing features 1, 2 and 3. Time has not permitted the measurement of sufficient grains to establish the shape of this and succeeding curves to the same level of accuracy as for those previously described. Figure 39 shows No. 1156 which appears to have a very large feature 2 but data do not adequately cover the region in which feature 1 would be presumed to occur. No. 1162 evidently has a Population A in the pebble size range and has a well developed feature 2. Insufficient data were obtained in the sand size range for this sediment.

Complex though the sediments just described appear to be, there is evidence of the existence of yet more complex ones. Figure 40 shows the elongation function curve of No. 1194 on two separate scales. The curve seems to show features 1, 2 and 3 in the usual manner, then rises yet again to a maximum at $p = 1.73$, $\frac{p}{q} = 1.74$ before becoming essentially horizontal. This curve is unlikely to arise from bad sampling partly because of the care taken to prevent this from occurring and partly because of its ordered nature. Some further evidence was later collected on sediments of this general nature. Figure 41 shows the plot, with two possible interpretations of the data, of No. 1193 which was closely associated with No. 1194. This sediment, insufficiently resolved, may be like No. 1194 but could be even more complex. Also in Figure 41 is shown the curve for No. 1153. This sediment apparently has feature 2 unusually accentuated.

Although the complexity of rheologic bed load sediments meant that a large number of them could not be studied in this general project, it can be concluded that:-

1. There is no doubt at all that rheologic bed load sediments can be distinguished from sediments of the ripple and dune stages by elongation function curves.
2. The elongation function curves of rheologic bed load sediments repeatedly show similar features, clearly manifestations of depositional processes rather than of provenance. They thus lend themselves to interpretation.
3. Most of these sediments appear to follow a standard pattern, showing features 1, 2 and 3 but some, apparently, are more complex.
4. Ordinary river gravels appear to differ from rheologic stage sands only in having a high concentration of pebbles in Population C.

Figure 42 shows the three populations plotted separately, by the method already described, for No. 1232, one of the rheologic bed load sands. The extremely steep gradient of the upper part of the Population B curve is doubtless responsible for feature 2.

Figure 43 shows the cumulative curves for Nos. 1230, 1232, 1235 and 1236. Each curve is split into sections ascribable to the constituent populations as indicated by the size-shape analyses (No. 1235 lacks Population C; the other three have it). Allowing for the coarse sieving tail of the Population A of No. 1235, all the Population A portions are very similar. The gradients of those parts of the curve ascribable to Population A are, of course, influenced by the amounts of other populations present. For example the gradient of No. 1232 is low partly because Population A is only 54% of the sediment. On the other hand, the gradient of No. 1235 is high partly because Population A is almost 80% of the sediment. Perhaps the most interesting feature of the sieve size distribution is the long, fine tail of Population B. The bulk of Population B, in each case, is composed of particles not many times smaller than those of the associated Population A's. The cumulative curves then show an abrupt change of gradient. (The impression gained during particle measurement was that a true size distribution would show an even sharper break). Thereafter, the rate of diminution with size becomes very small and the cumulative curve gradient, consequently, is very small too. All four curves, in fact, become virtually coincident at the fine end of the size distribution and all four sediments contain argillaceous material. It is extremely noteworthy that this major change in gradient in the cumulative curves always coincides with feature 1 of the elongation function curve. Figure 44 shows separate cumulative curves for the populations present in the four sediments.

Figure 45 shows the cumulative curve of No. 1153, a very coarse sand with a few pebbles in it. Figure 46 shows the separated population curves. It is noteworthy that the split, based on interpretation of the elongation function curve has segregated, as Population A, the only part of the whole cumulative curve that is smooth and almost linear. This population is known to be exactingly selected in terms of size and shape. Outside this range the entire cumulative curve shows a number of changes of gradient for the parts ascribable to Populations B and C. The Population B portion of the curve has the same major characteristics as those shown for the sands in Figure 43. Compared with sediments previously described the quantitative importance of Population A has fallen in this sediment to only 37% whereas Populations C and B have risen to 36% and 27% respectively. The sediment is, of course, bimodal with a mode due to Population A and one due to Population C.

Figures 47 and 48 show, respectively, the entire sieve cumulative curves for two gravels and the curves split into populations. These are typical traction clog gravels, the ordinary sandy gravels of rivers, consisting of pebbles packed in three dimensional juxtaposition and with their interstices packed with sand. Most of the gravels and conglomerates in the world seem to have this appearance. The amount of Population C in each is very large - 71% for No. 1228 and 72% for No. 1180. Population A forms 24% of

No. 1228 but only 13% of No. 1180. Population B forms only about 5% of No. 1228 but 15% of No. 1180 and, in this sample, is consequently more abundant than Population A. As with previous examples, the curves have a number of minor features in them outside the range attributable to Population A. Within this range (see Figure 48), the curves are smooth and almost linear. Population B again shows the marked change in gradient corresponding to feature 1 of the elongation function curve.

Figures 49 and 50 show cumulative curves for two more gravels, Nos. 1156 and 1160. The results are so like those already obtained that there is no need to describe them in detail.

The two sands with very complex elongation function curves (Nos. 1193 and 1194) were not split into populations because of inadequate understanding of their natures. Inspection of the elongation function curve of No. 1184 suggests that, if it has two Population A's (and two feature 3's) then the sieve mode of the two Population A's would occur at about 0.5 mm. and, perhaps, near 1.0 mm. respectively. It is of interest, therefore, that the undivided cumulative curve (see Figure 51) shows smooth, nearly linear portions in these two regions. Such parts of cumulative curves have come to be associated with Population A. Also in Figure 51 is the curve for No. 1193 about which less is known. In this curve two almost linear portions, with a break in slope between them, run between sieve sizes 0.35 and 0.60 mm. and between 0.60 mm. and 1.0 mm.

Finally, Figure 52 shows the elongation function curve for No. 1162 which, it will be recalled, showed a Population A in the small pebble size range but whose sandy portions received inadequate size-shape analysis. The identified Population A shows up well, running between 3.2 mm. and 8.7 mm. but another very similar feature runs between 0.23 mm. and 1.1 mm. This suggests the presence of another Population A.

Because the supposed "double" sediments, with, apparently, two Population A's, occurred only in rheologic bed load sediments and not in those of other stages, because they gave smooth, rational elongation function and sieve cumulative curves and because the care taken in sampling almost precludes their being mixed samples it is concluded, on the balance of evidence, that double sediments probably do exist.

Figure 53 shows all the separated Population A cumulative curves from rheologic bed load sediments. Allowing for the sieving coarse tail for Nos. 1235 and 1162 (due to paucity or absence of Population C), all the curves are nearly straight lines and all save one (No. 1228) have almost the same gradient. Some aspects of this consistency of results will be discussed later. Figure 54 shows all the separated Population B cumulative curves for the same sediments. All show the same features in that they consist of two main parts - a steeply sloping portion for the coarser sizes (only one example shows a significant break in this part of the curve) followed by a portion of low gradient running through the finer grades. Every sediment contained a proportion of argillaceous material. The curves for Nos. 1228 and 1160 are of the same general form as the others. The sediments merely contained more argillaceous matter than the others. The presence of fine material in the deposits of strong currents will be considered in a later portion of this thesis.

Figure 55 shows the Population C's for all the separated rheologic stage sediments. They are very variable, ranging from narrow distributions such as occur in ripple sands to huge size ranges that occur in traction clog gravels. Because the rolling power of these strong flows is so great, the nature of Population C, in all probability, largely depends on local availability of material. In this light, provenance becomes important and it is very interesting that many of the gravel Population C's are bimodal and there is nearly always a paucity of material in the 5-10 mm. size range. This represents the partial gap between the largest available granitic quartz grains and the smallest commonly available pebbles. The local detritus is, of course, nascent and much of the quartz is derived directly from weathering granite. According to

Moss (1966) the coarse granitic quartz soon breaks up and the greatest paucity moves down to the 2-4 mm. size range in more mature detritus.

One more technique was used on rheologic bed load sediments as a further check on the existence of discrete particle populations. The form of the elongation function curve with the comparatively short length of what is, apparently, the part of the curve due to Population A only, seems to suggest that the populations overlap considerably in terms of the long dimension. Moreover, feature 2 appears to be associated with low elongation function values of Population A but high values of Population B. Also feature 3 seems to be associated with high values of the elongation function for Population A and low values for Population C. If this is so, then distributions of the elongation function over small ranges of the long dimension may show signs of bimodality if drawn through features 2 or 3 but would not if drawn through ranges due solely to a single dynamic population. In preparation for such an investigation, distributions of the elongation function for granitic quartz (data derived from Moss, 1966) are shown in Figure 56 for grains in the long dimension ranges 0.2 to 1 mm. and 1 to 2 mm. These have relevance because the sediments being investigated here are dominated, in these size ranges, by granitic quartz. Linear probability paper was used for these plots. The curves are smooth but not linear.

Figure 57, prepared for the investigation, shows three hypothetical cases of distribution overlap such as could be supposed to occur in rheologic bed load deposits. Case 1 is of two distributions of about the same size with modes well separated ($\frac{p}{q} = 1.6$ and $\frac{p}{q} = 2.4$). Figure 58 shows the data plotted cumulatively on probability paper. Only a small inflection occurs in the resultant curve and the evidence for bimodality, were the data natural and subject to sampling errors, would be weak. Case 2 (Figure 57) shows a large and a small, flatter distribution with modes at 1.55 and 1.95. The resultant shows stronger signs of being derived from two distributions because of the sharp gradient change and the tendency of the curve to steepen again above the gradient change. Case 3 (Figure 57) shows a greater separation of a large and a small distribution so that the resultant is clearly bimodal. The cumulative resultant (Figure 60) shows the bimodality clearly.

A gravel, No. 1228 (elongation function curve given in Figure 36), is taken as a first example and a series of elongation function distributions, through successive small ranges of the long dimension are shown in Figures 61, 62 and 63. The first curve (p = 0.175 - 0.250 mm.) is in the fine tail of Population B and is like that of granitic quartz and, although skewed, shows no real sign of a break. The second curve (p = 0.250 - 0.350 mm.) is in feature 1 and shows no sign of a break either. The third curve (p = 0.350 - 0.475 mm.) shows a marked break as compared with the curves on either side of it. It is derived from the long dimension range of feature 2. The last two curves of Figure 61 return to the normal type and belong solely to Population A. In Figure 62 the first two curves, derived from Population A, are perfectly smooth although the grains in this range are becoming, on average, more elongated. The next three curves, covering the range p = 1.05 to p = 2.50 mm., are in the vicinity of feature 3. All show distinct evidence of bimodality. The first curve in Figure 63 is the last one in Figure 62, repeated for comparative purposes. Finally, the last two curves in Figure 63 are derived almost solely from Population C but the penultimate one possibly shows the waning influence of Population A.

Figures 64 and 65 show similar results for No. 1153 (elongation function curve in Figure 41). The first three curves in Figure 64 are through Population B. The second of these (p = 1.00 - 1.25 mm.) is through feature 1 but shows no sign of bimodality. The third, fourth and fifth curves cross feature 2. The third shows little sign of bimodality but the fourth and fifth evidently show a strong bimodal influence. In Figure 65 the first curve is through Population A, the second is through feature 3 and shows distinct signs of bimodality. The last four curves are in Population C and are smooth once more. The evidence thus provides strong support for the theory that features 2 and 3 result from data overlaps due to Populations A and B in the first case and to Populations A and C in the second case. Feature 1 evidently shows no sign of bimodality - merely a deficiency of elongated grains.

General Results for Natural Sediments

It is clear from the previous section that rheologic bed load sediments can be distinguished from ripple and dune stage sediments but that individual elongation function curves do not always distinguish between ripple and dune stage sediments. The present section reports work designed to reveal any differences between sediments of different stages by using plots involving data from groups of sediments. Also described are attempts to trace any relationships likely to shed further light on the formative processes of bed load sediments. It is recognised that the data are not comprehensive; mature materials, for instance, have not been covered save for the inclusion of four sands from an estuary in the study. Data from these act as a safeguard against the drawing of unwarranted conclusions from some of the plots.

Population B appears to be more environmentally sensitive than Population A which is evidently ubiquitous in bed load sediments. Also, in the ripple stage, the amount of Population B appears to vary with the grainsize of Population A. In the light of this, Figure 66 was prepared. It is a scatter plot of the weight ratio of Population A. That the plot comes near to placing the three stages in separate fields there is no doubt, as far as the local rivers are concerned. However, the position of the points for the estuarine sands, perhaps, serves as a warning that a plot of this type could only have wide application in areas of study where it is known that fine material is copiously available.

Figure 67 shows a further attempt to distinguish between ripple and dune sands on the basis of differences in the Population B fine tail. The ratio of the twenty percentile of Population B to its one percentile is plotted for the river samples, again, against the fifty percentile of Population A for the river samples. Separation occurs but not at a level permitting reliable individual sample diagnosis. The estuarine sands again plot away from the main dune field. However, the apparently greater tendency of ripple sands to keep out finer Population B particles than that of dune sands of the same coarseness, is shown. Figure 68 shows a similar plot but uses the ninety percentile of Population B instead of the twenty percentile. Again, separation occurs between the fields for the rivers but the estuarine dune sands plot well away from the river dune field.

Figure 69 is another scatter plot relating the size range of Population C to the coarseness of Population A. The finest particles of Population C, provided that material of all sizes are available, are always just larger than the largest particles of the associated Population A. One would expect the relatively weak currents laying ripple stage sands to have a lower rolling power than the somewhat stronger currents operating when sand of similar coarseness is built into dunes. Consequently, for the same rivers, all fed with hetrogeneous detritus, the data of Figure 69, in which the ratio of the ninety percentile to the ten percentile of Population C is plotted against the fifty percentile of Population A, would be expected to show some tendency to split with the highest values of the ratio associated with dune sands. Surprisingly, however, Figure 69 reveals little differentiation other than that ascribable to the differing size ranges of ripple sands and dune sands. Moreover, the highest values of the ratio are associated with ripple sands and the average value for them is 1.62 as against 1.45 for the dune sands.

Figures 70 and 71, following the same general theme as Figure 69, show, for ripple stage sands and dune stage sands respectively, the ratio of the ninety percentile of Population C to the fifty percentile of Population A plotted against the fifty percentile of Population A. As Figure 70 shows, the ripple stage sands show a somewhat featureless scatter with the ratio averaging 2.95. Figure

71 for the dune stage sands, shows a somewhat remarkable result in that a high negative correlation exists between the two quantities, the correlation coefficient giving a value of -0.714. The data are well fitted by a linear least square curve. Moreover, the average ratio is 2.55 - lower than that of the ripple stage sands. These seemingly anomolous results will be discussed later.

The sudden change in size range and abundance of Population B in ripple stage sands, occurs at a Population A sieve fifty percentile value of 0.25 mm. Figure 72 is a plot of the percentage of material finer than 0.063 mm. in Population B against the fifty percentile of Population A. That this effect is very sudden and extreme there is no doubt, especially in view of the fact that the sediments are from the same rivers and, in some cases, coarse and fine ripple sands were collected from points only a few yards apart on the same day. There can be little doubt that this plot manifests a very sudden critical condition associated with the size of Population A, that is, with the bed roughness.

On available evidence, particularly that presented by Moss (1962, 1963) and in the present thesis, the measurement of sorting for entire sediments does not seem justifiable save for empirical usage. The study of the size ranges of individual populations, however, seems more potentially useful. The resolution of sediments into their populations enables this to be done but the problem remains as to whether to use settling velocity or size as the most rational yardstick in each case. In particular, this problem affects Population A for there is evidence that properties related to settling velocity are of importance in its selection but also there is some evidence (Moss, 1963) that size is of some importance too by virtue of its influence on the ability of particles to be packed into a framework on the bed. In order to reduce the risk of missing valuable information, sorting measures based on both size and settling velocity (as closely as they can be approximated) are used here.

Figure 73 shows sieving results, used as an approximation of size sorting for the Population A's of ripple stage sands. To reduce errors caused by shape effects at the ends of the sieve size distribution (related, in the cumulative curves, to the abundances of associated Populations B and C) the sorting measure is based on ninety and ten percentiles. The ratio of the ninety percentile to the ten percentile of Population A is plotted against the fifty percentile of Population A. Again, there is a major difference between coarse and fine ripple sands. For a fifty percentile below 0.25 mm there is no discernible relationship between the two quantities. For the coarser ripple stage sands, however, the correlation coefficient has the very high value of + 0.762. The degree of selection with respect to size falls very rapidly with increasing mean size (the chosen measure, of course, grows larger as selection becomes less exacting). The sieve sorting, in fact, can evidently be predicted fairly accurately (within ten percent in most cases and twenty-one percent in the worst) by simply knowing the fifty percentile of Population A. Where S is the sorting and d the grainsize in millimetres, the least square empirical linear relationship obtained is:-

$$S = 1.405d + 1.291$$

An interesting application of this equation is to extrapolate it to, say, a value of 2 mm. for the sieve fifty percentile. This would give a Population A whose coarsest grains were over four times the diameter of the smallest. Hence, their volumes would vary by a factor of sixty or seventy. This, of course, would represent hardly any selectivity at all. Of course, natural ripple sands with Population A fifty percentiles coarser than about 0.7 mm. are rare and it seems probable that any coarser than 1 mm. do not exist. Possibly this sorting relationship has to do with the ripple stage - dune stage transition.

Figure 74 is a completely analogous plot to Figure 73 but for dune sands. The result is very different, however. The correlation coefficient, instead of being high and positive, is low and negative with a value of -0.325. On Figure 74 the coarse ripple stage curve is superimposed for comparative purposes. The interest in this plot is in its contrast with the analogous ripple stage plot.

Figure 75 shows the Population A sieve sorting of rheologic stage sediments treated in the same manner. Only ten values were obtainable but, of these, nine were between 1.84 and 2.21. The other (No. 1228) gave a value of 2.72. In view of the fact that the method used must be subject to some degree of error which unfortunately, cannot be accurately assessed, the implication is that, discounting the one odd value, the sorting of these Population A's is almost constant.

Settling velocity dispersion of Population A cannot be measured directly because a continuum of grains, with respect to this parameter, exists and one can only guess as to whether some grains present belong to Population A or not. Distal values from the mean can affect any dispersion measure relatively greatly. However, gaussian distributions with respect to settling velocity evidently give linear elongation function curves as does Population A. Also, it appears that, within obvious limits, the gradient of the elongation function curve varies with the dispersion of the settling velocity of a suite of grains. The larger the dispersion the lower is the gradient of the elongation function curve. Thus, it seems, in the absence of a direct measure, an approximation of the settling velocity dispersion could be attained by measuring the ratio between the gradient of that part of an elongation function curve for which Population A is evidently solely responsible and the gradient of the elongation function curve of a set of grains perfectly selected with respect to settling velocity and having the same overall shape characteristics. This could not be done exactly but the gradients for nearly perfectly sorted settling velocity suites were available, albeit measured at 25°C. Because the mean elongation function for most particle suites investigated appeared to be near 1.55, Figure 11b was used on the assumption that the Population A curve and the "ideal" curve would cross each other at an elongation function value of 1.55. The resulting ratio is called the "gradient sorting". The quantity should, ideally, range from low values for suites of particles poorly sorted with respect to settling velocity to unity for perfect sorting with respect to settling velocity. It would, of course, be possible for particles to be selected (e.g. by sieving) so that the gradient sorting would exceed unity.

Figure 76 shows the gradient sorting for the Population A's of ripple stage sands plotted against size. The fine ripple sands show no evidence of simple correlation and the coarse ripple sands are little better, giving a correlation coefficient of -0.180. This result contrasts very strongly with the sorting measure based on sieving. The dune stage sands, however, (Fig. 77) show a good correlation (R = +0.709) against the fifty percentile of Population A. It will be recalled that it was dune stage sands that gave almost no correlation with size in terms of sieve size. It has to be recognized, however, that three of the values for gradient sorting exceed 1.0 and two exceed 1.4. Thus, if the measure is reliable, a pure selection with respect to settling velocity cannot be taking place and an influence of linear dimensions may well be present. The sorting measure being used is, admittedly, not elegant. It is of great interest to note that whereas for coarse ripple sands, Population A sorting grows worse as size increases if measured by sieves, for dune sands Population A sorting grows better with increasing size but in terms of settling velocity. It is a great pity that more nearly perfect measures of both size and settling velocity have not been available.

Figure 78 shows the same plot for the rheologic stage sands. Obviously gradient sorting and size have little relationship whereas the sieve results implied almost constant sorting values.

By and large, there should be a correlation between sieve sorting and gradient sorting. Figures 79, 80 and 81, respectively show the gradient sorting plotted against the inverse of the sieve sorting used here. For the ripple stage the correlation coefficient is +0.649 and for the dune stage the value is +0.709. For the rheologic stage, of course, sieve sorting was found to be almost constant whereas gradient sorting varied markedly.

It seems reasonable to suppose that, if a quantity gives a meaningful plot against another, itself known to be meaningful in the same problem, then the first quantity will probably be meaningful too. These results lead to the tentative suggestion therefore, that if settling velocity (or parameters closely related to it) and size are both involved in the selection of particles for Population A, then size is, perhaps, relatively more important than settling velocity for coarse ripple sands, the relative importance is reversed for dune sands and size is the more important, once more, for rheologic stage sands.

Perhaps the most impressive feature of the examined natural bed load deposits is the fact that, although they are formed from heterogeneous detritus in turbulent water of varying discharge, they consistently follow a rational yet complex pattern in terms of the techniques used here to examine them.

A second conclusion is that, did these sediments not consist of Populations A, B and C the correlations shown in the present section could not have been achieved. All depend on the resolution of sediments into populations.

Thirdly, there seems to be some evidence that the ripple stage should be split into two - called here "coarse" and "fine". The major sedimentological criterion separating them is the grainsize of Population A.

Other conclusions will be drawn in a later section.

ARTIFICIAL BED LOAD SEDIMENTS

Introduction

A large proportion of the experimental investigations of bed load motion have, as a basic aim, the quantitative assessment of this type of transportation. The present investigation has a quite different purpose, the investigation of the differentiation of particle assemblages, during transportation and deposition, to form bed load sediments.

Whereas the investigation of natural sediments has many advantages, it is usually almost impossible to collect reliable moving bed load samples or to assess quantitatively the material fed to a natural flow from a source area. In a flume, however, material of known composition can be fed to the flow and any sediments formed can be compared with their parent materials. Moreover, it was thought that, in the present instance, the exhaustive techniques applied to natural sediments, if applied to artificial ones, would facilitate reliable judgement as to whether or not any artificially formed particle assemblage closely resembled sediments occurring in nature.

During the present study a small flume was made available by the Snowy Mountains Hydroelectric Authority at its Fluid Mechanics Laboratory at Cooma, New South Wales. The flume was not designed for sedimentological work and, at the time of use, was mounted in a manner that did not allow it to be tilted. It was, however, readily adaptable for the present work. It had one major advantage - plate glass sides of high optical quality. This enabled particle motion to be observed readily.

The flume had a steel frame, was 16 feet long, 15 inches wide and two feet deep. Flow entered via a Braithwaite tank and was controlled at the downstream end of the flume by a vertical louvre gate. The flume discharge fell into a gravitational system which returned the water, together with that from other hydraulic experimental set-ups, to a common sump. From here, water was recycled to experiments as required. A stilling tank was placed beneath the downstream end of the flume. This trapped some of the coarser particles but fine material, particularly silt and clay, tended to stay in suspension and to be repeatedly recirculated both through the flume and through other apparatus. Because of this attempts were made to reduce interference with other experiments to a minimum and work with strong flows was reduced to short bursts and, often, confined to periods when other apparatus was not in use. (It is stressed that these restrictions of usage were practised entirely on my own initiative. I was given permission to do exactly as I liked and the staff of the laboratory were helpful and accommodating to an extent that had to be experienced to be believed. The restrictions were merely a small return for their courtesy.)

Because of the nature of the recirculating system, suspended load could not be controlled. It could, however, be sampled just before the completion of a run so that the nature of the suspended load at the time the last sediments were formed on the bed was known.

Each flume run was commenced with a level bed, three inches deep, of the relevant experimental mixture. Replacement of lost bed load was carried out by hand through a large metal funnel at the upstream end of the flume. The feeding was carried out in order to maintain the average thickness of the bed. Needless to say, this method was not very accurate, particularly when the presence of dunes or ripples made the average thickness of the bed difficult to assess quickly.

Slope was measured with a micromanometer connected to the static head of a pilot tube. This method proved rather unsatisfactory. It was highly sensitive to temporal discharge fluctuations because of the time taken to use the instrument - often several minutes. Also, when dunes occurred, the resulting water surface undulations made slope measurement very difficult in such a small flume. In some runs, different structures and different grain sizes along its length would doubtless cause different slopes to occur along the flume. Moreover, many runs were stopped before an equilibrium between flow and sediment was attained and bed slope could not be controlled. Consequently, only a few slope measurements are considered reliable. Water temperature was recorded towards the end of each run and varied considerably from run to run.

Located at the 15 foot point (i.e. a foot upstream of the louvre gate) was a 3 inch high wooden barrier which terminated the sand bed at its downstream end. Nails were driven into the upper surface of the barrier at intervals of one inch in order to stop any large objects from reaching the louvre gate.

Discharge was controlled by an automatic system. For all runs the same discharge was used throughout. Having selected an appropriate discharge, the run was commenced with the louvre gate partially closed so that the whole flume rapidly filled. The gate was then gradually opened, thus reducing depth and increasing mean velocity until the desired bed load movement was attained. Runs were stopped by turning off the discharge and closing the louvre gate almost simultaneously. This filled the flume and reduced the mean velocity so that the bed was undisturbed save that a small amount of suspended load settled onto the bed. The flume was then very slowly drained in order to avoid erosion of the bed.

Flume Mixtures

Three flume mixtures were used. All were prepared from deposits associated with the Molonglo River. The bulk of the fine material was derived from the discarded washings from the gravel plant of Canberra Sand and Gravel Proprietary Ltd at Fyshwick, Canberra, A.C.T. This material was greyish in colour, consisting dominantly of quartz but with a significant proportion of metamorphic rock fragments. Most of the medium grained material was provided by a red sand, probably wind-blown but modified by pedological processes to such an extent that its grains were stained a bright reddish-brown colour. This sand blankets the lower topographic features along the course of the Molonglo River in many places in the vicinity of Canberra. Most of the coarsest sand grains were from a commercial concreting sand supplied by Canberra Sand and Gravel Proprietary Ltd. This sand had an overall grey colour, like the fine washings for, although quartz-dominated, it too had a proportion of metamorphic rock fragments. As ingredients for flume mixtures these materials had two major advantages. Firstly, they were composed of particles very like those forming the natural sediments investigated. Secondly, if any mixture of the red sand and either of the two other materials differentiated in terms of particle size, then the colour of the formed deposits on the bed would make the differentiation readily apparent.

The relevant characteristics of the three mixtures used are shown in Figures 82 and 83.

Mixture 1

Mixture 1 was the finest material fed to the flume. It was prepared from washings and red sand, from which the coarser grains had been removed by sieving. Owing to the sieving the elongation function curve of the mixture rises steeply in an apparently linear manner through the coarser part of the long dimension range. The sieve fifty percentile was 0.168 mm. 15% of the mixture was finer than sand and 2% was a coarse tail running from about 0.4 mm. to nearly 2.0 mm. The ratio of the ninety percentile to the ten percentile was 6.5 - far greater than that of any natural Population A.

Mixture 2

Mixture 2 was coarser than mixture 1 but was also prepared from fine washings and red sand. Less sieving was undertaken, however, and the elongation function curve was relatively flat, the minimum at p = 0.95 mm. and the positive gradient through the highest range of p being, in all probability, inherited from the red sand. The sieve fifty percentile was 0.231 mm. Again, coarse and fine tails were present, the former running up to about 3.0 mm. and about 12% of the mixture was finer than sand. The ratio of the ninety percentile to the ten percentile was 13.6 - about twice that of mixture 1.

Mixture 3

Mixture 3 was the coarsest used. It was prepared from red sand and concreting sand in equal proportions. Its elongation function curve was almost flat. The sieve fifty percentile was 0.477 mm. The coarse tail went up to over 5 mm. and about 3% of it was finer than sand. The ratio of the ninety percentile to the ten percentile was 12.5. For comparative purposes, the size analysis of the sand used by

Simons, Richardson and Albertson (1961) in their flume experiments has been inserted in Figure 83. Direct comparison, however, may be unwise because of the different method of size analysis used by these workers.

Runs with Mixture 2

Mixture 2 was used first. Each run will be described separately, together with the results given by samples taken from the bed after the run.

Run 2A

The object of this run was to study differentiation in a current just strong enough to maintain bed load motion of the mixture. Discharge was 0.72 cusecs, average depth 20.5 cm. and mean velocity 26.2 cm/sec. Temperature was 14°C. After four hours the discharge suddenly fell and the run was abruptly terminated without measuring slope or sampling the suspended load. However, owing to the interesting nature of the bed, samples were studied. Suspended load was not sufficient to impart visible colouration to the water.

After the run had proceeded for a few minutes incipient ripples appeared at the upstream end of the bed. These incipient ripples apparently differed physically from the asymmetrical ripples into which they developed. They had very low amplitudes and were apparently symmetrical in the current direction. That is, the bed surface became deformed into a series of very low-amplitude sine curves as seen in section from the cross-current direction. Simultaneously this area turned a bright red as against the reddish grey of the mixture. This meant, of course, that differentiation was taking place and that the coarser grains were being concentrated on the bed. Red ripples developed from the incipient ripples in the upstream portion of the flume. Transition to normal current ripples evidently took place when the amplitude of the incipient ripples reached a value that caused flow separation to occur and a tiny foreset to develop. Ripples seemed to inherit the wave length of their precursors. The downstream reaches of the bed became greyer and small incipient ripples appeared here too. These ripples were composed of sand very much finer than that at the upstream end of the flume. After both sets of ripples had developed fully it was observed that the upstream ripples were large (wave length about 4-5 inches) and high in relation to their wave lengths. They were composed of clean sand and appeared to be devoid of argillaceous particles or even fine sand. The downstream ripples, on the other hand, were of short wave length (about 2 inches) and were low in relation to their wave lengths. They were composed of fine, dirty sand.

Careful observation of particle motion revealed the manner in which this differentiation came to pass. Bed load motion was sporadic, apparently depending on the occurrence of velocity maxima near the bed. A few of the very largest particles were seen to roll over the upstream sides of the ripples and to pass over the crests, stopping either on the foresets or reaching the bottom of them. At the upstream end of the flume the movement of the particles making the bulk of the bed (red grains of medium sand) was observed. They moved in discrete jumps of length about three to thirty grain diameters but did not leave the bed by more than about three or four diameters, usually less. The most significant feature of the motion was, perhaps, the trajectories of individual grains. Some left the bed, accelerated horizontally and fell back to the bed but were often observed to decelerate markedly as they came within a diameter or so of the bed surface once more. Others would leave the bed, accelerate horizontally and return towards the bed but would decelerate (in terms of vertical motion) then rise again without touching the bed. Some would do this several times before finally touching the bed once more and coming to rest. It was observed that grains that had just landed were more likely to be moved on again than grains that had been on the bed for some time. Grains of this size would belong to Population A in a natural environment. Most of them were eventually deposited on the foresets of the ripples they had climbed. Some of these grains came to rest straight away but others were moved farther down the foreset or, sometimes, were even moved a few diameters back up the foreset. Minor avalanching was occasionally observed on the foresets. Grains interred in the foreset environment remained so until downstream migration of the ripple exposed them to the flow once more. Grains a little smaller than those concentrated in the ripples (watched individually, these were either clear quartz or dark grey rock fragments) exhibited undulatory motion still more. Individuals could be seen to move up the entire upstream slope of a ripple apparently without ever touching the bed or rising to more than two or three diameters from it. All the while they would oscillate up and down as they moved forwards. It was the behaviour of these grains on a surface of somewhat coarser ones that was the key to the differentiation during the run. As they reached the crest of a ripple they would, almost invariably, pass upwards into temporary suspension. If a ripple was viewed directly from the side, a plume of such grains could be seen passing downstream and upwards from the ripple crest. The length of individual excursions into suspension could not be discerned but the fine sand bed that formed on the lower half of the bed was undoubtedly due to the return of these grains from suspension. They returned in sufficient numbers to blanket the bed and to form ripples themselves in the same flow as that in which they were rejected farther upstream. Motion of grains on the small ripples at the downstream end of the flume was less easy to see but grains of the size making the ripple framework were seen hugging the bed very closely in low trajectories. It was obvious from the composition of the sands that they had "fine tails" and that the mechanism for repelling fine grains from the bed must have been less efficient in this downstream environment.

The sands forming the ripples were laminated, the laminae coming right to the glass sides of the flume. By the time the run was stopped the clean, coarse ripple sands had advanced to about half-way down the flume. Because of the variety of grainsizes and ripple sizes along the length of the flume, the run could not be claimed to have reached a steady state in a hydraulic sense.

After draining the flume a series of very small samples were taken from along the centre line of the bed. Three of these were studied. (Artificial sediments are numbered with the prefix "A"). A1 was from a ripple foreset in coarse red sand at 1'9" from the upstream end of the flume. Because the feed was supplied at about eight inches down the flume, the material could not have moved more than thirteen inches to make the sediment. Samples A4 and A7 came from 7'3" and 14'4" respectively. Both were from fine ripple foresets. All artificial sediments are described in Appendix 2.

Figure 84 shows the elongation function curves of the three materials. All three give curves of typical ripple stage sands. The elongation function curve for the original mixture is shown on the figure for comparative purposes. There is no doubt whatsoever that shape differentiation, even in such a short distance of transportation, was great. The size differentiation observed during the run is made obvious by the quantitative results. Figure 85 shows sieve analyses of the three sediments with those parts of the cumulative curves for which Populations A, B, and C were evidently responsible indicated. The curves are just like those of natural ripple stage sands. Differentiation is marked; whereas the feed had a fifty percentile of 0.231 mm. the three Population A's of A1, A4, and A7, had fifty percentiles of 0.497 mm., 0.155 mm. and 0.104 mm. respectively. Thus, in the same flow in a short flume, Population A's of twice or half the sieve size of the mixture formed and the ratio of the coarseness of A1 to that of A7 was 4.78. Hence the actual size range (in terms of volume) exceeded a hundred.

An interesting feature of the cumulative curves is that a slight excess of material around 0.200 mm. in diameter caused an irregularity in the curve for the mixture. The Population A's of A4 and A7 cross this size range without showing the feature at all. Such a result (and much other evidence) suggests very exacting selection of Population A grains. Another feature of the curve of A1 (a coarse ripple sand) is that material finer than sand, after only about a foot of transportation, was reduced to almost none at all from 12% in the mixture. A4 and A7 are fine ripple sands and contain about 3% and 17% of material finer than sand respectively.

Having a record of the nature of the original material fed to the flume enables enrichments of different particle size ranges to be measured. These must be used cautiously because none of them represent single stage differentiations. As is obvious from the description of the run, although A1, from upstream, probably differentiated from material close to the original mixture in composition, A4 and A7 came from areas bombarded by grains returning from temporary suspension after having been rejected by a bed forming A1 and others like it. (It is probably experimental luck that, according to the separations of data used, the Population A of A1 has a fine end at 0.286 mm. on the sieve scale whereas the coarse end of the Population A of A4 falls at almost the same value). The formation of sediments like A1 profoundly changed the composition of the transported material and this, in turn, affected bed load sedimentation downstream.

Figure 86 shows enrichment factors for the three flume sediments. Each sieve fraction percentage for a sediment is divided by the percentage of that fraction in the original mixture. (If depletion has occurred the "enrichment factor" has a value of less than one. In such cases, the name is retained for convenience although, strictly, enrichment has not occurred.) For A1 major enrichment (up to a factor of three) is associated with Population A. Its Population B shows a strong fall in enrichment down to about 0.01 at the sand-silt junction - consistent with the observed repulsion of small grains by the bed-flow intersurface. The other two sediments show enrichment factors of about four associated with Population A and up to three in the case of Population B. However, these factors doubtless partly result from a change of composition of the moving bed load as a result of differentiation upstream and temporary suspension. It does appear from the results, however, particularly that given by A1, that the processes forming Population A are strong concentrators of particles having a narrow size range.

From the results of this one flume run, a number of seemingly important conclusions can be drawn. How widely they are applicable will become apparent as more flume runs are described. In order to avoid repetition some are drawn here rather than later in the thesis.

1. In the coarse ripple stage the important force affecting potential Population A and Population B particles is, apparently, directed at right angles to the bed. This force is directly associated with the fluid-bed intersurface and its magnitude falls away rapidly with distance from the intersurface. The magnitude of this force apparently rises temporarily when turbulence fluctuations cause high velocities to occur near the bed. Potential Population A grains are picked up by this force and are, to some extent, buoyed up by it while horizontally directed fluid forces

move them downstream until they are able to repenetrate the field covered by the vertical force, often over the crest of a ripple. Potential Population B grains touched the bed less often as, being smaller, they were more continuously buoyed. This lift force was doubtless responsible for the rarity or absence of fine Population B grains in the bed. Many of these grains were "launched" into suspension from the ripple crests. This force loses some of its effectiveness, at least some of the time, for fine ripple stage sands and finer (argillaceous) material can enter the bed more readily. The observed mode of operation of the lift force leaves no reasonable doubt that this is the fluid-dynamic lift force associated with the velocity gradient near the bed in accordance with Bernoulli's theorem. Horizontal forces (impact and drag) must move the buoyed particles downstream but the lift force is the important and critical one.

2. Differentiation of bed load into sediments is very strongly marked and both bed load and sediments can be subject to very large changes in composition along a few feet of bed. Bed load composition must be continually changing and can seldom be assumed to stay constant in nature; nor can it be safely assumed that bed load and bed sediments will have the same composition.

3. Judged by this run, bed load sediments form, provided that the bed can be disturbed by the current, almost immediately in terms of space and time. The three

samples examined were virtually indistinguishable from natural sediments.

4. It follows that bed load sedimentation lends itself to experimentation to such an extent that quite small apparatus can be used to further understanding of the phenomena involved.

Run 2B

Run 2B was conducted in order to produce ripples at a greater intensity of bed load movement than was run 2A. Discharge was 1 cusec, average depth 20.1 cm., average velocity was 35.6 cm/sec and a single slope determination gave 0.00083. Temperature was 11.7°C. Suspended load (near surface) was 42.6 p.p.m.

Ripples, somewhat irregular, formed all over the bed from the start and the fine, temporarily suspended grains tended to be passed on out of the flume. The sands at the upstream end of the flume were only slightly redder than those at the downstream end and size differentiation was less marked. Particle motion was more intense than in run 2A but of the same general nature. Ripple wavelengths were 2 - 3 inches and height was up to 1 inch. Laminae in individual ripples varied markedly in thickness. The run was terminated after 2¼ hours. A sample of suspended load was taken from halfway along the flume just before the run terminated. Three samples of ripple foresets were taken along the centre line, A9 from 5'8", A11 from 12', and A12 from 14'.

Figure 87 shows the elongation function curves for run 2B. The sediment curves are shown together with those of the original mixture and the coarser grains of suspended load from just beneath the water surface. The sediment elongation function curves are of normal form and grainsize falls downstream. The curve for the suspended load has a steep gradient over the measured range and shows that the largest grains in suspension were highly elongated. Because the size limit of grains in turbulent suspension must be set by settling velocity, one would expect a curve of this form. However, temporary suspension may also contribute to the suspended load as observed in this and the previous run. Settling velocity, of course, would also be expected to place a limit on this. Thus, exactly what the suspended load represents in this case, in only 20 cm. of water, is not clear. The result does mean, however, that, over a considerable range of the long dimension, the more elongated grains tend to be in suspension whereas the more equant tend to remain on the bed. This effect may account for the elongation function curves of A11 and A12 reaching such low values in the Population A - Population B overlap range of the long dimension which, in each case, lies below the high part of the suspended load curve.

Figure 88 gives the sieve cumulative curves for the three sediments, the original mixture and the suspended load. A12 was unusual in containing 23% Population C. All three Population A's pass through the sieve size around 0.2 mm.

without reflecting the curve irregularity of the parent mixture. There was a small amount of argillaceous matter in all three sediments in spite of the fact that A9 was a coarse ripple stage sand (Population A fifty percentiles:- A9, 0.392 mm.; A11, 0.250 mm.; A12, 0.171 mm.). Also the three Population A's were, on average, less well sorted than those of run 2A (A9,2.89; A11, 2.87; A12, 2.13 as against A1, 1.94; A4, 1.97; and A7,2.20).

The sieve cumulative curve for the suspended load considerably overlaps the three Population A's in sieve size. However, the overlap may be smaller than it appears to be in terms of actual grains because the largest grains in the suspended load sample were elongated whereas the smallest in a Population A were equant.

Figure 89 shows the enrichment factors of the three sediments. A12 shows some enrichment in Population C, a point that will be discussed later. The three Population A's show maximum enrichments.

Run 2C.

Run 2C represented an attempt to produce dunes. Discharge was 0.93 cusecs, average depth 16.5 cm. and mean velocity 42 cm./sec. Slope was determined 0.0023 but, over dunes, in a small flume, this figure is not considered to be very reliable. Temperature was 11.0°C. Near-surface suspended load was 157.4 p.p.m.

Dunes formed from the outset. They were somewhat irregular, 1'6" to 2'6" in wave length and 1½" to 2½" high. The run was stopped after 2¾ hours.

During the run several differences were noted between movement in this stage and that in the ripple stage. Bed load motion was far more intense and particles moved more rapidly, often leaving the bed by several diameters. The rejection of grains smaller than those of Population A by the bed was marked. Plumes of these rejected grains could be seen passing into temporary suspension from the dune crests. Undoubtedly, during this run, material in temporary suspension reached the water surface. Avalanching, too, was highly developed, the foresets building up to angles often over 30 degrees, then avalanching suddenly down to about 25 degrees. Sunlight illuminated the water and it was possible to gain some idea of the flow pattern by observing the paths of the larger suspended particles. The flow pattern was very complex and subject to sudden temporal changes. Separation of flow occurred at the dune crests but the returning separated flow from one dune would tend to compete with the upward separating flow from the next dune downstream. The normal current on the surface of a foreset slope was upslope but, at times, a downslope current would suddenly flow for a few moments and this would often stimulate avalanching. This downward current was thought to be associated with the interference between the flow over the dune concerned and the returning separated flow from the next dune upstream. The initiation of avalanching apparently did not involve the lifting of the topmost grain layer but looked rather more like a shearing effect over the whole foreset slope.

Two foreset samples were studied, A14 from 3'6" and A16 from 8'0". Figure 90 shows the elongation function curves for these sediments together with those of the original mixture and the suspended load. The sediment curves are like those of natural dunes. In this run the more downstream sediment (A16) is coarser than the upstream one and lacks Population C. No overall size differentiation was noted during the run. All the sands were clearly coarser than the original mixture, the finer sand grains passing out of the flume in suspension. The suspended load curve is of interest for it appears to be S-shaped and compound. It is tentatively suggested that the sharp rise between $p = 0.05$ mm. and $p = 0.12$ mm. may be mainly ascribable to genuine turbulent suspension but that the apparent levelling out and further rise through higher values of the long dimension are due to temporary suspension.

Figure 91 shows the cumulative curves for the run. The fifty percentiles for the sediments were 0.361 mm. for A14 and 0.418 mm. for A16 as against 0.231 mm. for the mixture. Argillaceous matter was almost absent from both samples. The suspended load curve, like its elongation function curve, shows a break as if it could have two components.

Figure 92 shows the enrichment factors. They are similar to those of the ripple stage runs with marked enrichment in Population A and a marked diminution in Population B. The suspended load curve again shows a break.

Run 2D.

Run 2D was conducted in order to obtain dunes under conditions of more intense bed load motion than those experienced in run 2C. Discharge was 0.93 cusecs, average depth 13.9 cm., slope was determined as 0.0052 (though not considered accurate because measured over dunes). Mean velocity was 49.4 cm/sec. Temperature was 10.6°C. The run was stopped after 45 minutes. A suspended load sample was taken.

At first, the bed was level and horizontal laminae formed from a rather intense zone of bed load movement. However, the motion was not so intense that the bed could not be seen through it. This movement and resulting laminae mainly involved the finer fractions of the sand. After a few minutes, incipient dunes started to form at the upstream end of the flume from the red (coarser) grains of the mixture. These dunes rapidly took over the bed, averaging about 2'6" in length and 1½" in height with minor undulations on their upstream slopes.

Two samples were taken after the run, A20 from the outcrop of one of the early level laminae in a depression between the dunes and A21 from a dune foreset. Figure 93 shows the resulting elongation function curves. In spite of measuring a large number of grains from A20 the resulting curve showed no signs of features 1 and 2 and, in fact, gave a curve that typifies the fine ripple sand stage (the sand was much finer than any dune stage sand encountered). A21 gave a typical curve for a dune stage sand.

Figure 94 gives the sieve results for the run. The Population A fifty percentile of A20 was 0.171 mm. and that of A21 was 0.503 mm. - very coarse when compared with the mixture fifty percentile of 0.231 mm. Figure 95 shows the enrichment factors with typical enrichment in Population A and impoverishment in Population B.

Run 2E.

During run 2E it was hoped to form some rheologic bed load sands. Discharge was 0.93 cusecs, average depth was 11.3 cm. Average velocity was 76 cm/sec. Temperature was 8.8°C. In order to encourage rheologic bed load motion and because the flume would not tilt, the bed was sloped to fall one inch in 14 feet before the run. The run took only 15 minutes because of the large amount of suspended load being sent into the recirculating system. Slope was not measured. Suspended load was 407 p.p.m.

During the run the bed was not visible because of the formation of rheologic bed load and heavy suspended load. Through the walls of the flume could be seen a layer of intense bed load motion about 3 cm. thick with suspended load above it. The junction between the two zones was quite well marked. Late in the run some low dune foresets, about 1 cm. high and consisting of coarse red sand grains were seen through the flume wall advancing rapidly downstream. Some of these ceased to move when buried in finer (grey) level bedded sands.

Two samples from the run were studied, A27 from a tiny dune foreset at 9'0" and A29 from a level bed area at 14'3".

Figure 96 is a revelation. Size-shape analysis records the environmental difference between the two sands. Tiny though the dune foreset was, it had its own physical environment and its curve is like that of a natural dune sand. The level bedded sand, however, has all the characteristics of a rheologic bed load deposit. Its feature 1 is close to feature 2 and occurs beneath the steeply climbing suspended load curve. Feature 2 is exceedingly well developed and the part of the curve due to Population C is very like those of some natural rheologic stage sands too. The validity of feature 2 was checked statistically by comparing the mean elongation function for 180 grains making the feature with that of 240 grains on either side of it. The chances of its being absent are one in over 400.

Figure 97 gives the sieve results for the two sediments. A27, the dune sand, is typical again, containing 96% Population A and, in spite of the dense rheologic mass, the Population B contains almost no material less than 0.1 mm. in diameter. Presumably the lift generated by the dune bed, together with the separation effect, was able, locally, to hold the rheologic bed load mass off the bed, at least over the deposition area on the foreset. The fifty percentile of the Population A was 0.588 mm. - about 2½ times as coarse as that of the mixture. The cumulative curve for A29, on the other hand, is always close to that of the parent mixture. Only its Population A departs significantly and contrasts with the curve of the mixture over the same size range in being smooth as opposed to somewhat irregular. The sediment had only 33% Population A whereas Population C was 39% and Population B 28%.

Figure 98 shows the enrichment factors of the sediments. The Population A of the dune sand reaches a factor of 3½ whereas the rheologic bed load sand shows very little differentiation - its Population A reaches only 1.35.

Figures 99 and 100 show the distributions of the elongation function for small ranges of p for A29. These are compared with the nearest distribution obtained for the parent mixture. Reading from the left in Figure 99, the first curve is in Population B and differs little from that of the parent material. The second curve seems to show a slight deficiency of elongate grains and is in feature 1. The third curve passes through feature 2 and shows very strong evidence of bimodality whereas the parent material does not. This, of course, is the overlap zone of Populations A and B. The fourth curve shows some evidence of bimodality too. The fifth and sixth curves pass through Population A as it is becoming more elongated with increasing long dimension. They show gradual deviations from the parent material curves. The first two curves in Figure 100 are through feature 3 - the overlap zone of Populations A and C. Their forms bespeak such overlap. The last curve shows a much closer return to that of the parent material and no sign of bimodality. It is through pure Population C.

Finally, Figure 101 shows the elongation function distribution through the entire "bump" of feature 2, 360 grains in all. Bimodality is virtually unquestionable.

Runs with Mixture 1

Mixture 1, it will be recalled, was fine with a sieve fifty percentile of 0.168 mm. and contained 15% of argillaceous matter ($<$ 0.063 mm.).

Run 1A.

Run 1A was analogous to run 2A in that it was desired to obtain ripples under conditions of very gentle particle motion. Discharge was 0.5 cusecs, depth 18.3 cm., slope 0.000185 and temperature 15.6°C. Average velocity was

20.1 cm/sec and the run lasted $3\frac{3}{4}$ hours. No suspended load sample was taken.

The bed developed sedimentologically in a manner similar to run 2A. Red (coarse) sand captured the upstream end of the bed, forming ripples from the crests of which finer grains were launched into temporary suspension. Plumes of these grains were sometimes visible for 5 cm. downstream of the crests. Minor avalanching of coarse ripple foresets was common. Transportation of grains up foreset slopes was commonly observed. The coarse sand ripples grew quite large, 4 - 6 inches long and up to 2 inches high. During the run they advanced to about 2 feet down the flume. The remainder of the flume (downstream) was occupied by finer, dirtier sand formed into ripples 2 - 4 inches long but only $\frac{1}{4}$ to $\frac{1}{2}$ inch high.

Two samples from the run were studied, A30 from 1'9" (a coarse ripple sand foreset) and A35 from 12'4" (a fine ripple sand foreset). Figure 102 shows the elongation function curves for the samples together with that of the original mixture. The curves show no features not previously described save that A30 has an unusually long fine tail for a coarse ripple sand. Figure 103 gives the sieve results. A30 contained 34% Population B but only a minute proportion of it was less than sand size. The Population B of A30 has apparently inherited the form of the original mixture curve but neither Population A has inherited any of the irregularities of the parent mixture. Figure 104 shows enrichment factors for the two sediments. A30 shows typical Population A enrichment. A35 shows, also, Population B enrichment but this must largely have arisen from bed load changes down the flume bringing about a paucity of coarse material.

Run 1B.

Run 1B was conducted in order to produce ripples at a greater intensity of bed load movement than occurred in run 1A. Discharge was 0.75 cusecs, depth 18.5 cm. and mean velocity 30.3 cm sec. Temperature was 16.0°C. Slope measurement was unsatisfactory - possibly due to a discharge fluctuation during the measurements. Suspended load, just beneath the surface, was 24.2 p.p.m. The run was stopped after 1¾ hours.

In this run temporary suspension was well developed but it was observed that the bulk of the temporarily suspended grains occupied a zone about 7 or 8 cm. thick, near the bed. This left the top 10 cm. or so of the flow relatively free of suspended load - hence the small value for a near surface sample. Coarse (red) sand apparently occupied the whole bed after one hour, having displaced finer sands that had occupied the downstream portions earlier. Figure 105 is a photograph of the bed after the run. Ripples were 4 - 6 inches in wave length and up to 1½ inches high.

Five samples were taken from the centre line of the bed, all from ripple foresets. They were A36 from 2'2", A37 from 4'3", A38 from 7'4", A39 from 10'2" and A40 from 12'3". Figure 106 shows the elongation function curves for the sediments. The Population A's of A36, A37 and A38 follow closely the curve of the original mixture as if their formation was favoured by the pre-existence of an element in the mixture already resembling a Population A. A39 and A40 however, have much finer Population A's. Only after careful study did it become apparent that A40 had a fine Population A. Its Population C curve followed that of the original mixture and hence resembled that of a Population A. The suspended load curve is interesting in view of the observations made during the run. It is a simple, smooth curve consistent with there being a single mode of suspension near the water surface.

Figure 107 gives the sieve results. A40 has much Population C (25%). A36, A37 and A38 are coarse ripple sands with almost no argillaceous matter in Population B. A39 and A40 are fine ripple sands and have a little more argillaceous matter in Population B. Figure 108 shows the enrichment factors for the sediments. There is, in each case, enrichment in Population A but, interestingly, A40 shows signs of enrichment in Population C (as did A12 in run 2B). A37 shows some sign of enrichment in Population B. Of interest is the curve for the suspended load - straight and simple and consistent with there being a single suspension mechanism.

Run 1C.

Run 1C was intended to produce dunes as fine as possible in grainsize. Natural sediments had produced no Population A fifty percentiles for the dune stage finer than about 0.25 mm. The local rivers had yielded none with this quantity lower than 0.3 mm. Mixture 2 had produced a finest dune stage Population A with a fifty percentile of 0.361 mm. in spite of the fifty percentile of the mixture being 0.231 mm. Mixture 1, of course, being finer than this, should form finer dune stage Population A's if this could happen physically.

Discharge for the run was 1.02 cusecs, average depth 14.3 cm., slope (as measured over dunes) was 0.00164, mean velocity 52.9 cm/sec and temperature 15.8°C. Suspended load was 155.5 p.p.m. The run was stopped after 52 minutes.

The bed, soon after the start of the run, rapidly formed ripples with the typical attendant situation of expulsion of finer material in temporary suspension. After a few minutes some of the ripples at the upstream end of the flume became larger and more dune-like in form. This happened (or became noticeable) when the ripples were about five inches in wave length. The ripples grew into dunes, overtaking and burying others as they went, until the whole bed was covered by dunes 1 - 2 feet in wavelength.

The mechanism of dune growth was closely observed. Dunes formed only from the coarser (red) grains present and one dune could often be seen to capture nearly all such grains from the passing bed load, so that the next dune downstream received few suitable particles for its Population A's. The downstream dune could therefore move only relatively slowly but still functioned, for a while, as a launching ramp for the passing of somewhat smaller grains into suspension. Thus the upstream dune would rapidly overtake the downstream one until it reached a point where its separation flow passed over the crest of the downstream dune and, thereafter, the latter advanced no more as it was, most of the time, in the weak return (upstream) bed flow due to the upstream dune. At this stage a thin layer of fine sand (ripple stage?) would cover the downstream dune. This was composed of returned temporarily suspended load. The upstream dune would advance over the fine sand layer and finally over the crest of the downstream dune, thus increasing its height. This process would continue until some optimum dune height was reached that appeared to be related to the depth of flow. Figure 109 is a sketch of the result of this process as viewed through the glass wall of the flume.

Four dune foreset samples were taken after the run, A41 from 3'9", A42 from 7'6", A43 from 9'3" and A44 from 11'2". Figure 110 shows their elongation function curves together with those of the mixture and the suspended load. All are rather similar with their Population A curves tending to follow the rise at the coarse end of the parent mixture curve. All have long, fine tails due to Population B and these apparently show minima or run at low values over the long dimension range in which the suspended load curve is climbing to high elongation function values. The suspended load curve again shows a slight tendency to be S-shaped and there is no doubt that temporarily suspended grains occurred near the water surface in this run.

Figure 111 shows the sieve results for the run. The Population A fifty percentiles were:- A41, 0.319 mm; A42, 0.310 mm.; A43, 0.300 mm.; A44, 0.309 mm. Thus, in spite of the fine mixture, fine dune sands would not form. Any finer sand that did form merely made "level" laminae plastering the topography of dunes that were being overtaken. Although Population B went up to 39% of these sands, argillaceous matter was almost absent. The large amount of Population B in these sands may have been due, in part, to the large quantity of suitable material made available because only the coarsest particles were used in the making of Population A's. Figure 112 shows enrichment factors for the sediments. There is, as usual, strong enrichment in Population A and strong impoverishment in Population B.

Run 1D.

No natural fine rheologic sands were encountered in the present investigation. Nonetheless it seemed pertinent to try to obtain them from mixture 1. Because of the large amount of suspendable material in the mixture a short run only was undertaken. It lasted only eight minutes. Discharge was 1.02 cusecs, depth 9.5 cm. and mean velocity 79.4 cm/sec. Near-surface suspended load was 183 p.p.m. Slope was not measured.

As far as could be observed, the bed remained level throughout the run. Bed load movement was intense, a rheologic mass having formed immediately. On draining the flume, one small dune-like foreset feature was observed near the downstream end of the flume. It consisted of red sand grains - the coarsest commonly available to the flow. Otherwise, the bed was planar save for small structures that appeared to be current lineation marks. Many of these marks were associated with the presence of relatively large, individual grains on the bed. These were over 1 mm. in diameter and represented the extreme coarse tail of the mixture. In typical instances, such grains would have a small crescentic depression embracing them from their upstream sides and a little ridge running for a foot or more downstream from them and flanked by very slight depressions on either side. Some such little ridges occurred without associated large grains but it was not clear whether or not such grains had initiated the formative process then moved on. These structures appear to correspond with natural ones described by Karcz (1967).

Figure 113 shows the elongation function curves for the run. The suspended load curve is of interest because the bed was almost level and, hence, structures such as dunes did not aid the passing of particles into temporary suspension. Also, the strong current brought a large proportion of the suspended load size range into the conveniently measurable range of size-shape analysis. The curve, for the finest measured range of the long dimension, appears to be nearly horizontal, but, for the higher values of the long dimension, apparently climbs steeply and smoothly to high elongation function values. This is consistent with an upper size limit being being set by settling velocity. The curves for the two sediments appear to be somewhat unusual and are best considered in conjunction with the sieve results, shown in Figure 114. A45 shows a minimum like feature 1 in the elongation function curve but a large proportion of the sediment consisted of material of the size range involved in this apparent feature. For higher values of the long dimension there appears to be a weak feature 2 followed by another Population A. The cumulative curve for this sediment was not divided into populations because it closely resembled the supposed double sediments found in nature. A47, at first, appeared to be another double sediment but was found to fit the normal sediment pattern fairly well. There appears to be a weakly developed feature 2 at a long dimension value of 0.27 mm. (most of the elongated grains required to accentuate the feature would, obviously, be in suspension). This is followed by an apparent Population A, a feature 3 and then a minimum followed by a further climb in elongation function values for the highest range of the long dimension. This last feature is thought to represent Population C which could have been inheriting features of the parent mixture. Figure 115 shows the somewhat small enrichment factors for the two sediments. Later in this thesis these two sediments will be discussed once more against the general background of rheologic bed load sedimentation.

Run 1E.

Run 1E was conducted in order to obtain current bedded foresets in the ripple stage on a somewhat larger scale than that associated with the ripples themselves. A dune-like feature was built across the flume from the mixture. The crest was raised $4\frac{1}{2}$ inches above the normal bed level and its overall length was 4 feet. It had a gentle upstream slope but its downstream slope was at the dry angle of repose of the mixture. A low discharge of 0.42 cusecs was introduced to the flume. Initially water poured rather violently over the foreslope of the feature and the height of the crest above the normal bed was reduced to 3½ inches by erosion. Also a scour pit formed downstream of the foreslope. After the flow had settled down, a depth of about 3 inches over the crest was maintained. Ripples formed on the upstream slope of the feature to within 8 inches of the crest and the bed downstream of the feature became covered with ripples too. A strong return current flowed beneath the separation zone and vortices were common in this area. These were of sufficient strength to stimulate more than usually violent bed load motion. Foreset laminae accrued steadily on the downstream side of the feature. The foreset angle was near 25° and the laminae did not develop tangential lower contacts. Transportation on the foresets was common, some grains moving downslope and some upslope. During the run the crest of the feature was lowered by about half an inch. The run was stopped at a time when the scour pit was reached so the vertical height was about five inches. The run lasted 2½ hours.

A single foreset sample, A50, was studied. Figures 116, 117 and 118 shows its characteristics. It is a typical fine ripple stage sand whose most interesting characteristic is the absence of Population C (rolled grains), possibly due to the bed slope.

Runs with Mixture 3

Mixture 3 was considerably coarser than the other two used. Its sieve fifty percentile was 0.477 mm., close to that of the sand used by Simons, Richardson and Albertson (1961), but the size range of the present mixture was much greater.

Run 3A.

The object of run 3A was to examine the effect on the bed of a current that would barely cause bed load motion and to try to collect samples of sediments, the constituent particles of which had moved only an inch or two from their original positions on the bed. Discharge was 1.06 cusecs, depth was 33.7 cm., slope was very small but not reliably determined, mean velocity was 23.4 cm/sec and temperature was 21.7°C.

During the period of initial filling of the flume some very small dune-like foresets appeared on the bed. After the commencement of the main run, these ceased to move and, in fact, tended to disappear. Bed load movement was very low and suspended load was 122.4 p.p.m. The largest particles commonly present (diameter 3 - 5 mm.) rolled intermittently over the smaller. Often they would be excavated from the bed by scour around them before being set in motion. Once moving, the larger they were, in general, the faster and farther they moved before stopping. Grains around the model size of the mixture moved very little. Their individual movements were rolling when over surfaces of fine sand but a very gentle form of saltation, reaching only a diameter or so above the bed, when on particles their own size. Fine sand moved more readily in low-trajectory saltation. A feature of the run was that ripples did not form or even start to form in a period of 2½ hours. Instead, a feature resembling current lineation formed, as it had under rheologic bed load in run 1D. Again, these little ridges tended to run straight dowmstream forming wakes to the larger particles in the bed. Whether or not any difference existed between the little ridges formed under the two sets of circumstances is not yet known. Certainly the general appearance of the bed was similar after both runs.

Two samples were taken after the run. One, A52, was a fine, level bedded sand. The other, A54, was from a very thin veneer of somewhat coarser sand the modal particles of which were thought to have moved only very short distances (perhaps an inch or two) from their original bed positions. Figure 119 shows the resulting elongation function curves. That of A52 is the typical curve of a fine ripple sand although it looks somewhat unusual because of the scale used. That of A54 could be the curve of either a ripple stage or dune stage sand, but it does give a sediment curve even after so little motion. Figure 120 shows the sieve results for the two sediments. A52 was actually one of the finest sediments produced in the flume experiments with a Population A fifty percentile of 0.122 mm., equal to the nine percentile of the mixture. A54 had evidently differentiated little from the parent mixture but already shows a deficiency of largest particles and of fine particles.

The suspended load of this run was of interest because depth was great, velocity low and there were no structures of significant size on the bed. Almost all the load (taken near the surface) was argillaceous and its elongation function curve rises steeply and smoothly with no tendency to be S-shaped. Figure 121 shows the enrichment factors of the two sediments. The Population A of A52 reaches the very high value of 7.0 but A54 shows, as would be expected, little enrichment.

Run 3B.

Ripple stage sands with Population A fifty percentiles coarser than 0.7 mm. are apparently rare. Because the mixture contained about 33% of material coarser than 0.7 mm. and because enrichment factors of about 3 were commonly reached in the formation of Population A's from the two finer mixtures it was of interest to see if a rippled bed could be made from mixture 3. Run 3B represented such an attempt. Discharge for the run was 0.75 cusecs, average depth was 21.5 cm. and mean velocity was 26.1 cm/sec. Slope was not measured because of bed heterogeneity and temperature measurement was inadvertently omitted though this was probably near to 21°C. The run lasted 2 hours.

During this run bed load motion was more intense than in run 3A. In the first few minutes incipient ripples started to form from the finer (red) grains. After these had become asymmetrical and had reached a height of about a quarter of an inch and a wave length of about $2\frac{1}{2}$" a dune suddenly commenced to form at the upstream end of the flume. This was composed of coarse, light grey sand. Apparently, the larger this dune grew, the faster it grew. Little material was taken into the interstices of this coarse sand and almost all medium and fine sand grains were buoyed rapidly up the upstream slope and launched as a plume just above the separation zone. So thick was this motion of temporarily suspended grains that the downstream bed area to which most of them returned could be readily discerned. Their return to the bed altered the composition of the bed load making it finer. This effect evidently stimulated ripple formation. The red ripples quickly grew to about 5 inches in wave length and ½" to 1" high. The addition of feed to the flume to replace that taken away downstream by the current evidently stimulated the formation of a second dune, upstream of the first. When feed was added, a cloud of fine material passed along the bed and some of this entered any dune laminae forming at the time. Dune "capture" by overtaking was frequent and, by the time the run was stopped, the upstream 6½ feet of the flume was occupied by three major dunes and a few local lesser dune foresets. The remainder of the flume was occupied by ripples. Dune sands apparently fined downstream, the downstream dune being formed of visibly finer sand than the most upstream one. Although the dunes were, physically, current bedded, no current bedding could be seen in some parts of them. Figures 122, 123, 124 and 125 are photographs taken of the bed after the run.

Two samples (A55 and A58) were taken from the upstream dune and one (A61) was taken from a ripple foreset. Figure 126 shows the elongation function curves for the three sediments. The huge difference in grainsize between A55 and A61 is obvious. The sieve results (Figure 127) further show this very strong differentiation. The Population A fifty percentile of A55 was 1.16 mm. as against 0.477 mm. for the parent material. This differentiation had taken place in eight inches of travel. The ripple sand (A61) had a Population A fifty percentile of 0.272 mm. All three sediments contained almost no argillaceous matter. Figure 128 shows the strong differentiation in terms of enrichment factors.

Run 3C.

Run 3C was conducted in order to obtain dunes. Discharge was 1.08 cusecs, depth was 20.4 cm/sec., mean velocity was 27.5 cm/sec. and temperature was 20.7°C. Slope determination could not be made reliably. The run lasted $1\frac{1}{2}$ hours. Suspended load was 165.0 p.p.m.

Dunes started to form immediately at the upstream end of the flume and ripples of finer sand formed over the rest of the bed. Size differentiation was less extreme than in run 3B. After $1\frac{1}{2}$ hours the whole bed was occupied by four large dunes. It was noticed, that if a dune approached to within 2 feet (crest to crest) of the next downstream, then overtaking and capture always took place. Each dune was composed of finer material than the next one upstream.

Two samples were taken, both from foresets. A64 was from 4'7" in the top dune and A66 was from 13'3" in the fourth dune. Figures 129, 130 and 131 show the characteristics of the sediments and the suspended load. Both samples lacked Population C but this may have been coincidence. Also, both were very low in Population B and argillaceous matter was virtually lacking.

Run 3D.

Run 3D was conducted in order, if possible, to make a material closely resembling a typical sandy river gravel - a traction clog deposit as postulated by the author (Moss 1963). The immediate question was to determine whether or not, in accordance with the postulate, these gravels form when sand in rheologic bed load motion is supplied with large objects, such as pebbles, which it can roll but cannot lift, and the gravel results when some large objects stop, blocking the path of others, so that a deposit of both sand and pebbles forms.

Mixture 3 was used for the run, and a bed fall of one inch over the length of the bed was made before the run commenced. Discharge was 0.75 cusecs, depth was 8.2 cm. and temperature was 20.0°C. Slope was not determined. Average velocity was 67 cm/sec. After about ten minutes, pebbles, ranging from 8 to 50 mm in diameter, were dropped into the upstream end of the flume at the rate of about one per second. The run lasted 25 minutes. Suspended load was not sampled.

The bed load was in rheologic movement throughout the run. During the first few minutes standing sand waves appeared with remarkable rapidity, occupying the upstream half of the flume. The addition of sand feed seemed to stimulate their formation. Later the bed became flat again and remained so for the rest of the run, as far as could be observed. Because of the rheologic bed load movement and heavy suspended load, little could be seen of the pebbles after they entered the flow. Judged by observation through the glass walls the dense bed load layer was about 4 cm. thick.

After the run was stopped the bed was smooth and planar with no pebbles visible in spite of the fact that about fifty pounds of them had been added to the flow. Probing just upstream of the sand barrier (into the top of which, it will be recalled, nails had been driven in order to stop large objects from reaching the louvre gate) revealed a deposit of pebbles and sand but this had, of course, been caused to form by the nail barrier. Further probing of the bed revealed that it was almost pebble-free save for one area from 5'6" to 7' and occupying only the right-hand half (looking downstream) of the flume. This deposit, occurring beneath a veneer of sand, consisted of approximately equal amounts of sand and pebbles and ended abruptly upstream, downstream and laterally. It apparently reached the glass wall of the flume but no pebbles could be seen touching the flume wall. About half the pebbles fed to the flume were present in the deposit. Beside it, medium sands had apparently formed under the same general flow conditions. This sort of occurrence is what would be expected from the postulate of Moss (1963).

Two samples were taken from the bed, both from 6'6". One was, of course, a gravel (A67) and the other was from the medium sand (A70) beside it. Figure 132 shows the elongation function curves for the gravel (on two scales) and of the sand. There can be no reasonable doubt that the gravel was genuine. Its curve shows features 1, 2 and 3 and the long, coarse tail, due to Population C. The sand curve shows feature 1 and a rather poorly developed feature 2. It had little Population C and its Population A was very much finer than that of the gravel. Both curves, however, show the feature 1 minimum at the same long dimension value. Figure 133 shows the sieve results. The fifty percentile for the gravel was 14.5 mm. whereas that of the sand was 0.38 mm. Thus, one was 38 times as coarse as the other in terms of sieve diameters or about 5,500 times as coarse as the other in terms of particle volume. Yet they formed side by side in the same flow. Knowing something of their method of formation it is more apt to state that the gravel had a Population A fifty percentile of 0.677 mm. and the sand an equivalent figure of 0.386 mm. The gravel was actually 19.6% Population A, 18.3% Population B and 62.1% Population C whereas the sand was 69.0% Population A, 15.3% Population B and only 16.7% Population C. The very strong bimodality of the gravel size distribution was partly due to the known paucity of 2 - 10 mm. material in the material fed to the flume. Figure 134 shows the enrichment factors for the two sediments (the figures for the gravel are converted to apply to mixture 3 only). As with other investigated rheologic bed load sediments, enrichment factors are relatively low.

Having established that a gravel can be laid by quite a weak current that may be also laying sands, it was unfortunately, not practicable to test the second postulate of Moss (1963), i.e. that the strength of a current required to remove a deposit of this nature may be very much greater than the strength of the deposit that laid it.

Run 3E.

Run 3E was conducted in order to obtain more rheologic bed load sediments from mixture 3. Discharge was 0.75 cusecs and depth was 8.2 cm/sec. Slope was determined as 0.0156, mean velocity was 67.1 cm/sec and temperature was 20°C. Suspended load was 208.2 p.p.m. Before the start of the run the bed was made to drop 4 inches over its entire length but this gradient was reduced by the flow during the run. Duration was about 15 minutes. The general conditions of the run were very similar to those of run 3D. A suspended load sample was taken from halfway along the flume.

Three bed load samples were taken from the plane bed revealed after the run, A73 from 3'0", A75 from 7'0" and A77 from 11'0". Figure 135 shows the elongation function curves. The suspended load curve evidently climbs in a straight and simple manner. The curve for A73 shows little sign of feature 1 and feature 2 is apparently present but poorly developed. When it is considered that this sediment was collected from a point reached by the current only 1½ seconds after entering the flume and that the rheologic bed load was apparently not moving much slower than the average speed of the current, it is little short of amazing that a sediment formed at all. A75, formed after about 3 seconds of current travel, gives a very different curve. Features 1, 2 and 3 are very well developed and the curve is, apparently, exactly like that of a natural sand laid from rheologic bed load. It is noteworthy that feature 1 occurs beneath the region in which the suspended load curve is climbing steeply. A77 shows additional features to those exhibited by A75 and, in fact, resembles the supposed natural double sediments. It does show a minimum in the same place as does A75 and something very like a strongly developed feature 2 at p = 0.73 mm. Between these two points there *could* occur another Population A.

Figure 136 shows the sieve results. A73 is, apparently, not greatly different in composition from the parent mixture. A75, however, has differentiated considerably. A77 has not been subdivided but two nearly straight portions of the curve suggest two Population A's. All three curves show a marked gradient change in the vicinity of 0.105 mm. Figure 137 shows the enrichment factors. A73 shows little enrichment but A75 shows strong enrichment in both Population A and the coarser fractions of Population B. This may be due to deposition of coarser grains in the upstream part of the flume. All three curves fall away sharply for low sieve size values under the portion of the suspended load curve that is climbing steeply with falling sieve size.

Where clear evidence is available, as for A29 and A75 there can be little doubt that feature 1 is related to the transition, with falling grainsize, from bed load transportation to turbulent suspension. Almost certainly, over a certain range of the long dimension, the more inequant grains will be mainly in suspension and the more equant will be predominantly in the bed load. If no other sedimentary phenomena interfere, then the Population B curve of any formed bed load sediments will reflect this transition by showing a minimum in their elongation function curves. This feature will be discussed at greater length later.

Figures 138, 139, 140 and 141 show the elongation function distributions for A75 over small ranges of the long dimension. These are compared with distributions for the parent mixture over closely similar long dimension ranges.

They are described for successive ranges of the long dimension:-

0.069 - 0.130 mm.: The sediment curve resembles that of the parent mixture.

0.130 - 0.206 mm.: The sediment shows a deficiency of elongated grains. The curve passes through feature 1 and the missing grains were probably in suspension.

0.206 - 0.261 mm.: This curve is still, apparently, influenced by feature 1. It, again, shows a lack of elongated grains.

0.261 - 0.288 mm.: This is in Population B and is close to the curve of the parent material.

0.288 - 0.329 mm.: This curve is still in Population B and resembles the parent material curve.

0.329 - 0.384 mm.: This curve apparently shows a slight deficiency of elongate grains, possibly because very equant grains of Population A are becoming numerically significant.

0.384 - 0.419 mm.: This curve resembles that of the parent material.

0.419 - 0.573 mm.: The curves in this range all show evidence of bimodality. They pass through feature 2 which, it is supposed, is due to data from fairly equant Population A grains and elongated Population B grains.

0.573 - 0.613 mm.: This curve still shows some evidence of bimodality.

The next three curves (second, third and fourth in Figure 140) are in Population A and merely show increasing gradational deviations from parent material curves as

Population A grains become more elongated with increasing size. The remaining three curves show the incoming of Population C while Population A persists, its grains ever more elongated, as the long dimension increases.

General Relationships for Artificial Sediments

A few general relationships of data from artificial sediments were plotted although it was recognized that data were quite inadequate for a general assault on major problems concerned.

It will be recalled that argillaceous matter was found to be virtually absent from coarse ripple stage sands whereas varying, often large, amounts were present in finer ripple stage sands. This result was shown in Figure 72. In this figure the percentage of argillaceous matter in Population B was plotted against the fifty percentile of the associated Population A. Figure 142 is the same plot repeated for artificial ripple stage sediments. Clearly the effect is present. Only two coarse ripple stage sands have over 6% argillaceous matter in Population B and one of these is A54 - a sediment representing only an inch or two of bed load transportation. This result seems to suggest that there is not so much an absolute refusal of the bed to accept argillaceous matter but that each fine grain has a low probability of being taken into the bed. Thus, after a ripple has advanced a few wave lengths, argillaceous matter would be reduced to a very low-level unless a large amount arrived from upstream. The fine ripple stage sands (fifty percentile of Population A less than 0.25 mm.) all have 14% or more argillaceous matter in Population B.

Figure 143 represents a plot of sieve sorting (ninety percentile divided by ten percentile) of artificial ripple stage Population A's versus the fifty percentile of Population A. The curve obtained from natural sediments is superimposed on the plot. Of the artificial coarse ripple sands, some have apparently reached the curve but others lie above the curve (that is, they are less well sorted than natural ones of the same mean size). A54, probably the least transported Population A, had a sieve sorting value of 4.84 and was far less well sorted than any natural sediment encountered. These results suggest that a certain amount of "turnover" in the form of repeated depositional and erosional cycles along the bed, is required to produce optimum sorting in coarse ripple stage Population A's but the distance required to achieve this is probably measurable in feet, not miles.

Figure 144, a plot not obtainable in nature, shows sieve sorting for ripple stage sands against distance down the flume. Discounting the locally produced A54 which does not represent transportation down the length of the flume there is, strangely, an apparent general tendency for sorting to grow less exacting down the flume. However, the correlation coefficient has the low value of +0.376 and several factors may contribute to this result. It is noted for instance, that the often poorly sorted fine ripple stage sands were usually taken from the downstream portions of the flume.

Coarseness of Population A relative to coarseness of the feed mixture for ripple stage sands is of interest. Figure 145 shows the ratio of fifty percentile of Population A to that of the mixture plotted against the distance down the flume of the sample. This is, of course, only a semiquantitative plot because runs were stopped arbitrarily and, were any run allowed to continue long enough, the entire bed would have been covered by the coarsest commonly available grains. The only point a long way from the curve is for A52, formed in run 3A, in which distance along the flume was of little consequence. The trend line shows the extremely strong differentiation encountered under the conditions stated for the runs. Typically the Population A at the top end of the flume is about twice as coarse as the mixture but fine deposits form downstream as a result of the strong upstream differentiation.

Figure 146 shows the gradient sorting of the Population A's of the flume ripple sands plotted against grainsize. The plot is little more than a random scatter as happened for the natural equivalents of these sands.

Figure 147 shows a strong correlation between gradient sorting and the inverse of sieve sorting. The correlation coefficient was + 0.788.

Figure 148 shows the sieve sorting of Population A versus the percentage of Population A in the artificial ripple stage sediments. Oddly, with the exception of the point for A54 from run 3A, there appears to be a good positive correlation between the two quantities. One would expect the presence of foreign grains (Populations B and C) to tend to disrupt the framework of Population A and to make sorting less exact. However, the reverse is evidently the case. This could be due to the fact that, for a given bed load, a well sorted Population A makes more bed load grains outside its size range immediately available for deposition than would be possible for a poorly sorted Population A.

Figure 149 shows the percentage of Population B plotted against the ratio of the fifty percentile of Population A to that of the mixture. There is obviously little relationship between the two quantities, probably because any provenance limitations that could be placed on the amount of Population B present were overidden by stronger limitations due to fluid-dynamic lift on the bed. A similar plot for Population C is shown in Figure 150. This figure does, in fact, apparently show a negative correlation. This is to be expected. All evidence suggests that the amount of

Population C in a sediment, given that its upper size limit is set by the strength of the current, depends on local availability. In the flume runs, a relatively fine Population A would have more material coarser than itself locally available than would a relatively coarse Population A. The coarsest grains that can exist in a ripple stage Population C are of interest but the small samples used make plots of this of doubtful reliability. Figure 151 shows the ratio of the ninety percentile of Population C to the fifty percentile of Population A plotted against the fifty percentile of Population A. A slight tencency to follow the trend of the natural equivalent plot is shown in that the ratio is generally higher for fine ripple sands.

Dune stage sands gave rather less well ordered plots than did ripple stage sands and some of the plots seem to bring about groupings of material according to parent mixture rather than according to other parameters. The sieving practised in order to bring about an upper size limit to mixture 1 seems to have influenced sorting of dune stage sediments derived from it. Figure 152 gives the usual plot of sieve sorting versus grainsize. Admittedly, the natural dune stage sands gave a wide scatter for this plot but the four dune sands from mixture 1 in Figure 152 give a closely spaced group plotting a long way from the main field - with sorting values around 1.6. Figure 153 shows the gradient sorting plotted against grain size. Again, the sediments from mixture 1 form a separate group whereas the sorting from the other two mixtures is uniformly poor. It will be recalled that the equivalent natural plot showed a high positive correlation between the two quantities. The results seem to suggest that more bed load turnover (deposition and erosion cycles as dunes pass a point) is necessary in the dune stage than in the ripple stage and that the flume runs had not reached a stage wherein dune Population A sorting had been brought to its usual natural level. Those derived from mixture 1, however, had, so to speak, a flying start for Population A development due to the size-shape relationships of that mixture.

The dune stage plot of the ratio of the fifty percentile of Population A to that of the mixture against distance of transportation down the flume is shown in Figure 154. There is little sign of correlation largely because dune Population A's always tended to form from the coarsest material commonly available and because the downstream reaches of the flume were often occupied by level bedded or rippled material. Only two dune Population A's, both from the coarsest mixture, were finer than their parent materials. The four points from the coarsest mixture do show a grainsize diminution downstream and such effects were, of course, qualitatively observable during the runs.

Figure 155 shows sieve sorting of dune Population A's versus distance down the flume. There appears to be little relationship between the two quantities. As previously implied, the flume was probably too short to achieve significant progressive sorting improvements.

In rheologic bed load flow, because both Populations B and C can form large proportions of a sediment, bed load differentiation is less extreme than in the ripple and dune stages. Almost all available particles can enter a lamina in one role or another. This was shown to be the case in the flume results. Once bed load and suspended load are separated, a short flume is probably as good as a long one in producing sediments in this stage. It will be recalled that natural Population A's deposited from rheologic bed loads gave extremely consistent sieve sorting results. The ratio of the ninety percentile to the ten percentile was found to lie between 1.84 and 2.21 in nine cases out of ten. The six separable artificial Population A's all give values between 1.75 and 2.25 (Figure 156). This is essentially the same result as that achieved in natural deposits and seems to imply that size is very important in the particle selection. Figure 157 shows the gradient sorting for the same sediments plotted against grainsize. There appears to be no ordered arrangement of the points - the same negative result as that obtained from natural deposits.

Figures 158, 159 and 160 show three plots used in attempts to differentiate between natural ripple, dune and rheologic stage sands repeated for artificial sediments.

The weight ratio of Population B to Population A versus grainsize is shown in Figure 158. Separation is less good than it was in the natural deposits. Figures 159 and 160, based on the size range of Population B and confined to ripple and dune sands, show little more differentiation than could be ascribed to the differing Population A size ranges.

For reasons already given, plots involving hydraulic parameters have been largely avoided in such a general survey as that at present being undertaken. However, two tentative attempts have been made, largely in view of observations suggesting that fluid-dynamic lift is of primary importance in moving grains, at least in the ripple and dune stages. Figure 161 is a scatter plot for the three stages in the flume, mean velocity being plotted against the fifty percentile of Population A. It does show quite good separation of the three stages but three dune sands seem to plot well away from the main field. If fluid dynamic lift is of importance then, in a shallow flume, the ratio of current velocity to depth should, perhaps, be a more significant parameter than mean velocity alone. Figure 162 is a scatter plot of this parameter against grainsize. On the plot lines can be drawn separating fields for the three stages with only one dune sand well away from the main dune field. As the general evidence suggests that really fine dune sands do not exist a very tentative line has been drawn directly between fine ripple and rheologic fine sands. Also, a demarcation line has been drawn between fine and coarse ripple sands. A diagram of similar type that was known to be reliable would, of course, have many uses.

Note on Suspended Loads

Many workers, including Moss (1962, 1963) have tended to regard suspended load as behaving essentially independently of bed load and vice versa. The present work makes it clear that somewhat complex relationships exist between the two loads and exchanges of matter between them are frequent.

It seems clear, from the flume experiments, that suspended load consists of two sets of particles involved in suspension over sandy beds in bed load movement. Bagnold (1966) quoted examples of apparently anomolous, bimodal suspended loads. There is essentially permanent suspended load distributed throughout the flow and, secondly, there is a temporarily suspended load occupying a zone above the bed but only reaching the surface in shallow flows.

The evidence suggests that the permanent suspended load has its upward size limit fixed by settling velocity, that it pervades the flow, including the zone of bed load movement, and that, save when repelled from the bed by some mechanism, it can enter bed load deposits. It enters the bed of fine ripple sands in significant quantities, is usually sparse in, or absent from, coarse ripple sands and dune sands but occurs in significant quantities in deposits laid by rheologic bed loads.

Temporarily suspended grains are usually larger than those in permanent suspension but evidently also have their upper size limit set by settling velocity or a related parameter. Roughness elements are important in the production of this load in ripple and dune stage transportation. In the first place, such grains, smaller than the Population A grains making the surface, appear to be buoyed up by vertically directed forces on the upstream slopes of ripples and dunes. Thus they are kept in transportation until they reach the structure crests where they are launched into temporary suspension. Downstream, they tend to return to the bed and, apparently, can do so if either the structures causing their suspension no longer exist beneath them or, if, by settling in sufficient numbers, they can blanket the bed, thus reducing the diameter of the bed roughness elements and changing the hydraulic environment. In either case the grains that were in temporary suspension pass into bed load motion themselves. The elongation function curves of some suspended loads resemble those of sediments. The fact that this is so may facilitate the seeding of a Population A on the bed from returned suspended load in the size range over which the suspended load curve has a steep positive gradient.

Suspended load samples from the flume runs can be interpreted in terms of the foregoing reasoning. In run 3A the flow was deep, the average velocity low and the bed remained level. Near-surface bed load had a coarse ninety percentile of 0.06 mm and its elongation function curve rose in a smooth, apparently linear manner. This was probably closer to being a permanent suspended load sample than any other taken. For fast, flat bedded runs, 1D, 2E and 3E, coarse ninety percentiles of the suspended load of 0.168 mm, 0.183 mm and 0.162 mm were recorded. Their elongation function curves climb fairly evenly with increasing long dimension. Run 1B, in which a gentle current flowed over ripples, had a sieve ninety percentile of 0.252 mm and for run 3C, over dunes, the equivalent figure was 0.259 mm. Over structures, the suspended load elongation function curves tend to be S-shaped.

Without any doubt, apart from any effects on the properties of water (effective density, apparent viscosity) suspended load and bed load are intimately related.

Summary of Flume Results

The conclusions tentatively reached after the first flume run seem to be generally justified after fifteen runs with three different feed mixtures. All the sediment types encountered in the local streams were reproduced in the flume. Probably, all have been made in flumes by earlier workers but this is the first time that sufficiently exhaustive methods of study have enabled such a conclusion to be drawn with reliability.

Perhaps the most important conclusion is that, as suggested by Moss (1963) bed load sediments form virtually immediately, in an advanced stage of development and from whatever material is available, in response to prevailing hydraulic conditions. A few feet or even a few inches of transportation are adequate for the formation of these sediments. These results mean that a very large amount of information concerning this type of sedimentation can be acquired as a result of quite simple experimentation.

The experiments have left no doubt as to the reality of Populations A, B and C. It must be heavily stressed that these populations represent real natural entities, not an arbitrarily defined way of handling granulometric data. They were discovered, not invented. The key process in bed load sedimentation is the formation of Population A. Its importance is only challenged when traction clog gravels form and Population C becomes relatively important. Because of the very consistency of Population A, its immediate value in environmental analysis is overshadowed by the usefulness of Populations B and C, particularly the former.

It seems extremely probable that fluid-dynamic lift is the important fluid force causing bed load motion, at least in the ripple and dune stages.

Almost certainly, when bed load transportation and sedimentation is ultimately satisfactorily quantified, bed loads rich in pebbles will have to be given separate treatment because of their potential for forming traction clog deposits.

Suspended load, both permanent and temporary, is involved in bed load sedimentation and becomes involved in bed load sediments.

Because of the exacting requirements in terms of shape, size and quantity, when grains are selected to make a Population A, bed load sediments and moving bed load above them must always be different, save by rare chance circumstances. Also, for the same reason, composition of moving bed load must be for ever changing, whether flow conditions are changing or not.

MAIN CONCLUSIONS

General Remarks

It is abundantly clear, from factual results alone, that bed load sedimentation is exceedingly complex in nature. One can state certain fundamentals such as temperature, the size of grains, the viscosity or the density of water but, beyond this level, there are no independent variables. The flow affects bed configuration and vice versa. Material in suspension affects bed load sedimentation which, in turn, can affect material in suspension. The complex interplay of processes manifests itself, not so much as a continuum, but as a series of complex situations each separated from others by critical conditions. What happens at a point on the bed of a stream is often intimately related to events that have just taken place upstream. However, one phenomenon involved in these interactions stands out for its consistency. It is the formative process of Population A which takes place at the flow-bed interface. It is largely this process, as yet inadequately understood, that gives sedimentological approaches a chance to add to our knowledge of bed load sedimentation.

The concept of environment, as used here, is essentially physical. The flume is regarded as approximating physically, a section of any shallow unidirectional current and the rivers too, may be regarded not just as rivers but as examples of natural unidirectional currents. In essence, therefore, the work applies just as much to many shallow marine environments as to a river. However, it will be recalled that the rivers studied were fed largely with granitic detritus and it seems likely that, for some other rivers and for many marine environments, either provenance or regional sorting effects may bring about shortages or excesses of materials of some size ranges. Locally, for instance, there could be much larger concentrations of suspended clay in flows than have been encountered in the present study. In flume studies, beds in the coarse ripple sand stage have been found to accept clay grains from suspension (Simons, Richardson and Haushild, 1963). In such circumstances, bed load sedimentation could possibly differ greatly from the general picture given here. On the other hand, flows forming sediments from freshly weathered granitic detritus can be taken as a sort of standard with which other cases can be usefully compared.

Particles In and Under Shallow, Unidirectional Water Flows

In effect, all shallow unidirectional flows may be regarded as boundary layers. For nearly all situations in which bed load transportation takes place, flows are entirely turbulent. However, there is some evidence that the laminar sublayer and, more particularly, its thickness relative to the size of the particles lining the bed, may be of considerable importance (Shields, 1936). That bed load motion is, at least, physically possible in laminar flows was shown by Bagnold (1955).

Matter is carried by unidirectional currents by an array of mechanisms interrelated in such a way that changes in nature or concentration of one type of load can affect other types of loads. Firstly there is the load in true solution which can affect the physical properties of water and, through adsorption, can affect the behaviour of the finer argillaceous particles via such phenomena as flocculation. Fine material of the suspended load can affect the behaviour of the water via its effect on apparent viscosity and density and is also capable of reducing bed roughness by filling interstices between large particles and of cementing larger particles, thereby increasing the magnitude of the force required to set them in motion. The study of Simons, Richardson and Haushild (1963) demonstrated the existence of such effects. Further possible effects of fine suspended load can be suggested. Zenz and Othner (1960, p.116) state that small amounts of fine material, added to fluidised beds of coarser material, markedly decreased the viscosity of a fluidised mass. It is evident from the present work that some fine material must be present in moving rheologic bed loads. In the flume, the rheologic mass covered the bed entirely yet significant quantities of fine material occurred in deposits from this mass which must, therefore, have contained at least some such fine material. Such possible effects on bed load transportation seem to warrant investigation. For immediate purposes it is important to recognise that fine, essentially permanent, suspended load is distributed throughout the flow and is always available for involvement in bed load sedimentation.

In rivers, in general, essentially permanent suspension involves material up to about 0.063 mm in diameter - the arbitrary sand-silt junction. Strong flows, however, can bring the upward size limit well into the sand grades. Silt and clay are normally distributed fairly evenly throughout the flow in rivers.

Temporary suspension was of sufficient importance to affect bed load sedimentation considerably in some of the flume runs. Its maximum size and concentration appear to be related to the occurrence of flow variations around macroscopic bed features. The flow over ripples and dunes is particularly effective in launching such grains into suspension, the particles being carried upwards by the separated flow over, and downstream,of the crests. As far as could be judged from the flume runs, a series of dunes or ripples could cause an essentially continuous zone of temporarily suspended grains to be formed, the effects of successive individual dunes or ripples overlapping considerably. Vertically, however, temporarily suspended grains became rarer and smaller upwards from the bed. The results of Einstein, Anderson and Johnson (1940) for a natural stream appear to show the same pattern. In some flume runs, temporarily suspended load was, apparently, present just below the water surface. As previously mentioned, the return of temporarily suspended grains to the bed can markedly affect bed load sedimentation.

Bed load movement involves saltation, rolling and sliding of grains when grain motion is individual but normal saltation gives way to another form of motion when the trajectories of saltatory grains commonly cross each other. The suggestion of Moss (1963) that particles of sand or pebble size cannot roll or slide unless they rest on a surface of particles smaller than themselves, seems to be confirmed by observations, made in both natural environments and the flume, during the present investigation. If a particle rests on others its own size or larger, then it must be lifted from the bed if it is to be moved downstream. In the ripple and dune stages, it appears that rolling and saltation grade into each other. Obviously a fluid dynamic lift force that is capable of lifting a Population A grain will lessen the effective weight of a grain only two or three times as large to a significant extent and thus facilitate rolling.

As far as sedimentation is concerned, the distinction between saltation on the one hand and rolling and sliding on the other is extremely important. Grains that can be lifted from the bed, provided that they are exposed thereon, can be removed upwards from their positions and dropped elsewhere by the current. Such grains can thus surmount other grains or obstructions in their paths. Saltation is essentially three dimensional and allows exacting sorting processes to operate as is the case when Population A is built. If a particle can only be rolled or slid, however, it must always be in contact with the bed so that, if it is stopped by an obstruction or another stationary grain, there it must stay until either the current becomes strong enough to lift it or the obstruction is removed. Such motion is not conducive to good sorting as is obvious from the results given by the Population C of gravels.

In view of the above considerations saltation is regarded as any movement of a particle clear from the bed that does not lead to suspension. The simplest type of motion (other than a lifting which only allows the grain to drop back to its original position) is a simple lift to a diameter or two above the bed and a return to the bed in a horizontal distance of a few grain diameters. This is commonly observed in coarse ripple stage sedimentation for grains qualified to enter the local Population A. A more complex motion is observed, particularly for grains somewhat smaller than the local Population A grains, in which a grain moves along, apparently in a series of bounces, but does not actually touch the bed. Such grains appear to be bouncing on the fluid dynamic lift barrier. In the dune stage, for medium sands, saltation is more violent, grains achieving much higher trajectories but, for coarse sand which evidently has no ripple stage, gentler motion can be observed in the dune stage. Saltation affects rolling and sliding particles because, by building Population A, it creates a bed surface over which larger particles can be rolled. Saltatory transportation can also affect suspension by temporarily adding relatively coarse particles to the suspended load. Saltation, in its gentler form appeared to persist for very fine sand grain sizes in the flume.

Normal free saltation is limited in terms of near-bed grain concentration. Obviously, with half the grains rising and half falling, a stage must be reached wherein intergranular collisions become important. In a series of important papers Bagnold (1954, 1955, 1956, 1966) has studied the motion that ensues. He calculated that, at nine percent of solids, intergranular collisions become inevitable. Also, he was able to predict the hydraulic conditions for the onset of bed load transportation as a rheologic mass of grains. Most energy transfer in the mass is probably due to momentum transfer from grain to grain. Bagnold demonstrated the existence of an overall dispersive pressure, due to such collisions, within the mass. That sediments formed from a rheologic mass are quite different from those formed in the ripple and dune stages is demonstrated by the present results. During the flume runs, the bed and bed load within a few millimetres of the glass flume wall could be observed but the physical conditions here may be atypical. The motion of individual grains in the main rheologic mass could not be descried. The bed surface would have hundreds of grains added to a small area of, say, a square centimetre, in a second or so and a similar number removed in the next second. As soon as a grain left the bed, it became mixed with thousands of others in the rheologic mass and was no longer identifiable. Typically the rheologic mass was a few centimetres thick in the flume runs. It behaved like a dense fluid as far as any large objects placed in its path were concerned. Pebbles and perhaps also boulders in very strong flows, must be partially or wholly immersed in the rheologic bed load mass which must thus be regarded as a transporting agent for large particles.

Rolling was commonly observed during the flume runs in the dune and ripple stages. Sliding was observed comparatively rarely. The rolling grains were invariably a little larger than the associated Population A grains. They, clearly, were added to the sediment as Population C. They were observed to differentiate down foreset slopes, the largest of them often rolling to the foot of the slope. An apparently strange feature of both flume and natural sediments was that the rolling power of currents in the dune stage appeared to be no more than that in the ripple stage in spite of the difference in current strength. In nature, dune stage sands were observed to contain clay galls up to three centimetres in diameter but, of course, the specific gravity of these objects was very low.

In the ripple and dune stages rolled particles are relatively small and usually sparse. They apparently have little effect on other transportation phenomena.

When the rheologic bed load is developed, flow is usually supercritical in very shallow water but it is doubtful whether or not supercritical flow is necessary for the sudden major increase in the transporting power of rolled objects associated with this form of transportation. Fahnestock and Haushild (1962) placed individual pebbles and boulders in a flume over a bed of medium sand. In lower regime conditions, the objects did not roll downstream but tended to roll over into scour pits formed around them. Under upper regime conditions, however, rolling downstream occurred, the objects often accelerating to about half the speed of the current. Moss (1963) considered the rolling of large particles on a stream bed and stressed the importance of the particles' own kinetic energy (due to both rotation and forward progression) in this type of motion. It was also suggested by Moss (1963) that rolling was responsible for the formation of traction clog gravels and that these deposits could exercise major control over bed configuration and channel form. If this is so, rolling could, in aftermath, affect all other forms of transportation of solids. Certainly, the roughness, associated with stationary pebbles and boulders lining the bed, is capable of causing temporary suspension of sand. In the Murrumbidgee, at low flow stages, a beaker full of water, taken from just below the surface of two feet of water and downstream of boulders resting on the bed, would often contain sand grains over a millimetre in diameter. In alluvial streams, the bed load forms some complex equilibrium with channel size and form. Thus the bed load has a major role in exercising indirect control over suspension.

Independence of suspended and bed loads was assumed by Moss (1963). That this conclusion was not altogether justified is apparent from the foregoing considerations of particle motion and the factual results herein reported. Even if suspended load does not occur in bed load deposits, there is a possibility that the suspended load may affect the sedimentation in some way.

In one flume run, a rheologic bed load deposit and a dune stage deposit formed at the same time and in the same flow. The exact flow conditions under which changes in bed form occur cannot yet be stated. Consequently, in the present work, it seems safer to refer bed load deposits to the intensity of bed load motion rather than to the flow itself.

The Three Populations

Udden (1914) considered the possibility of the coexistence of simultaneously formed dynamic populations in sediments. His "primary maximum" coincided, roughly, with Population A and his "secondary maximum" with Population C (Moss, 1963). That Population B also existed was, at least, implied by other workers (Krumbein and Aberdeen, 1937, Einstein, 1950). Size-shape analysis (Moss, 1962) made the existence of the three populations more readily apparent and Moss (1963) suggested modes of formation for them. Since then other workers (Chappell, 1967, Friedman, 1967) have made use of this explanation in the interpretation of the results of granolometric analyses.

The present investigation has provided a large quantity of new information on the three Populations and an attempt will now be made to explain the nature of each separately and in greater detail than was previously possible.

Population A and Laminae.

Because of their apparent intimate relationship Population A and the laminations of bed load deposits will, for convenience, be considered together.

Population A is ubiquitous in water bed load deposits having been found in all of nearly three hundred samples, ancient and modern, natural and artificial, investigated by the writer. Most sediments have a single Population A; a few, deposited from rheologic bed load, appear to have two. The presence of Population A is, almost certainly, diagnostic of bed load sedimentation. Population A makes the framework of the deposits in which it occurs. Typically it forms 50 - 100% of deposits. The development of ripples and dunes must clearly be intimately related to Population A - flow interaction. These structures can consist of well over 90% Population A. Population A's known natural size range, in terms of its mean sieve size, is from 0.07 mm to 30 mm or so but there is no reason to suppose that its natural size limits have been reached in either direction. Individual particles present in the population range from 0.04 mm to about 50 mm in diameter. This represents a diameter range of over a thousand. In terms of composition of constituent particles, diversity can also be great. Quartz, shell fragments and rock particles can all be dominant constituents (Moss, 1962). One Population A found consisted entirely of garnet grains (Moss, 1963). A very similar suite of grains to Population A forms the bulk of all investigated wind-laid sands.

Essentially, Population A consists of an exactingly selected suite of particles differentiated from the saltatory grains or the rheologic bed load. The suite of grains ranges continuously from relatively small, equant ones to somewhat larger elongated ones. Its size distribution is strongly unimodal. Invariably, whatever the source material, Population A yields a linear elongation function curve. The garnet Population A (Moss, 1963) had smallest particles that were nearly perfect rhombic dodecahedra and hence very equant. The medium sized grains consisted of somewhat distorted dodecahedra and the largest were very distorted dodecahedra and angular fragments bounded by fractures. In another Population A (Moss, 1962, Sample No. 262) the smallest grains were mostly equant quartz grains and rock fragments, the next largest were often shell fragments and the largest were echinoid spines. Artificial Population A's not only develop their essential characteristics as soon as bed load deposition starts but, should the size distribution of the parent material being fed to the flow show an irregularity in its cumulative curve and a Population A form over the size range containing the irregularity, then, in the cumulative curve of the Population A, the irregularity will have disappeared. It is unfortunate that sieve analysis is not sufficiently exacting, as a size analysis, to enable apparent precision of selection, evidently involving not only size and shape but also the relative numbers of particles of different sizes and shapes, to be followed more closely. Sieve cumulative curves of Population A's, if allowance is made for shape effects at the end of sieve size distributions, nearly always plot as nearly straight lines on semilogarithmic paper.

Unfortunately, although the formative process making Population A is obviously the key process in the making of bed load sediments, the very lack of variation shown by this population makes it difficult to study. Geographically it occurs in rivers, on beaches and offshore. Physically, it persists throughout the ripple and dune stages and survives the transition to rheologic bed load deposition with little change. It would, from the evidence given in the preliminary section of this thesis, be easy to conclude that Population A is simply a selection of particles with respect to settling velocity in water. Not only that but it has also been shown that a suite of grains making the aeolian equivalent of Population A more closely resembles a suite of particles of equal mass.Whereas viscous effects are relatively important in bed load sedimentation in water, momentum exchange is relatively far more important in air (Bagnold, 1941) and such a result as this is to be expected. That this experimental result is very interesting and of importance is undeniable but any supposition that settling velocity, or other quantities closely related thereto, are all important in the formation of Population A can be immediately destroyed by reference to the existence of the garnet sand (Moss, 1963) already mentioned. The Population A of this sand consisted entirely of garnet, a minor constituent of the source material of the stream from which the sample was taken. The stream was, in fact, supplied with a continuum of detritus ranging upwards to boulders in size and consisting dominantly of quartz and of rock particles of specific gravity close to that of quartz. Were Population A selected simply with respect to settling velocity, this particular Population A could never have been formed in the river. All we could expect would be a mixture of garnet grains and quartz and rock particles two or three times larger in terms of diameter. Clearly, although a Population A closely resembles a suite of grains selected with respect to settling velocity, some other factor or factors influence the selection of particles during the formative process.

On the evidence then available, Moss (1963) concluded that Population A probably represented a compromise between the fulfilment of packing requirements and the bringing together of particles of similar hydrodynamic properties. It was also suggested that the aeolian equivalent of Population A (Type 5 sediments) represented a compromise between similar packing requirements and the bringing together of particles of equal mass. Because Population A is known to hold a close resemblance to suites of grains of constant settling velocity, over a considerable size range, there can now be little doubt as to the importance of a parameter related to settling velocity. If fluid dynamic lift is important in lifting grains from the bed (and there can be little doubt that it can be, in view of evidence already given), then the existence of such a parameter is readily explicable. Fluid dynamic lift would merely have to be balanced against the gravitational force tending to hold the particle on the bed. The influence of packing phenomena was envisaged by Moss (1963) in terms of a sort of stacking compatibility in terms of size, shape and grain orientation that allowed maximum mutual protection from the flow (and, more particularly, from fluid dynamic lift). Grains could land from saltatory leaps in perched positions or in depressions, or be equant and easily packable or inequant and usually left exposed. They could be comparatively large and thus be left exposed or comparatively small and be easily lifted. They could be dense and difficult to lift or less dense and easy to lift. They could land in favourable or unfavourable orientations (hence apposition fabric would develop). After a grain arrived on a bed area all these factors would influence whether it stayed or not as would the probability of a turbulence fluctuation capable of lifting it during the time it was exposed on the bed. Thus, time would be involved in the sense that, during deposition, a grain must stay on the bed in a relatively exposed position until the accumulation of other grains around and, finally, above it, gives it increasing protection and, finally, complete immunity from being lifted. Thus the rate of sedimentation is important in that, the slower it is, the more exacting the selection that can be achieved. During erosion, of course, however well positioned a grain may be, the removal of others around it will expose it increasingly to the flow so that it will finally be lifted. Using these considerations, it was possible to explain, for instance, the pure garnet Population A mentioned above. If, by chance, a few garnets could land together to make a tiny patch on the bed, then any quartz grain landing on the patch and hydraulically equivalent to the garnets (and hence larger) would be left in a highly exposed position and would, almost certainly, be removed. A newly arrived garnet would require less protection and usually receive more. It would be more likely to stay. Thus could a Population A consisting of pure garnet differentiate on the bed.

In the light of the considerations given above it seems reasonable to suppose that hydraulic and packing effects would have some sort of balance of influence during the formation of a Population A and that, in different physical situations, this balance could, perhaps, alter so that either hydraulic or packing influence may be the more important. The results of the sorting studies of natural and artificial Population A's now seem to be at least partially explicable qualitatively.
In the coarse ripple sand stage transportation is slow and sedimentation rate is low. This situation should favour packing phenomena and hence size. In natural samples, sieve sorting (which actually involves both size and shape when applied to suites of particles with the size range of a Population A) gave a good correlation with grainsize; gradient sorting (based on settling velocity) did not. A linear curve was fitted to the natural data. When this curve was superimposed on the flume sample data plot it was noticed, for mixture 2, that a coarse ripple sand formed by very gentle

motion in run 2A gave a point lying almost on this curve whereas equivalent samples formed in run 2B, with faster transportation, gave inferior sieve sorting values. In the dune stage, transportation and deposition are relatively rapid and the natural samples gave a good correlation between gradient sorting and grainsize but there was little sign of correlation between sieve sorting and grainsize. In the rheologic bed load stage the mechanism of motion is quite different. It seems reasonable to suppose that, with deposition taking place beneath a barrage of fast moving grains, any grain left projecting above bed level would probably be knocked back into a state of motion and the balance would, perhaps, once more swing back towards packing phenomena, involving size and shape. Both natural and artificial rheologic bed load deposits, in fact, gave almost constant sieve sorting values for Population A whereas gradient sorting was highly variable.

Other evidence that non-hydraulic parameters are important arises from consideration of the distribution of Population A's in space and time. Population A's of the same grainsize can form in flows of widely varying strengths. Also the same flow can form Population A's of widely varying grainsizes. Considerable variation even occurs between associated Population A's in the same stage - even in adjacent laminae. A Population A remains unchanged during the deposition of a single lamina and laminal changes are

Population A changes (Moss, 1963). Observation of particle motion in the ripple and dune stages confirms the views of Jopling (1966) and Kuenen (1966) that the time scale of flow-variations due to turbulence is much shorter than that of laminal changes (or Population A changes). Moreover, individual laminae run the whole length of foreset slopes and flow conditions can hardly be the same near the crest and near the toe. Another seemingly odd property is that where Population A's are forming on both foresets and associated areas of level beds, there seems to be little or no difference between examples from the two situations. The effect of flow maxima near the bed appears to be to stimulate motion of particles making the bed surface without changing the size of the particles involved in bed sedimentation. Explaining these observations in terms of purely hydraulic phenomena would be rather difficult. If, however, one uses the suggestion of Moss (1963) and Kuenen (1966) that grains already forming the bed surface are able to exert major control over which grains are added to the growing framework, these difficulties of explanation fade away.

Another property associated with Population A is the virtual absence of graded bedding of the type involving a gradual decrease in modal size upwards. Were its selection purely hydraulic, one would expect such bedding to be common, especially where currents had undergone temporal deceleration. There is much evidence that a forming Population A exerts a sort of buffering effect on hydraulic variables during its formation.

Evidence of packing phenomena also arises from the fact that Population A shows an apposition fabric (though avalanching may destroy it) and the considerable variations of bearing power of beach sands (usually pure Population A) of apparently similar granulometric characteristics.

The various stages of deposition seem to be associated with changes in the nature of Population A. This population will therefore be discussed stage by stage.

Fine ripple stage. Sediments formed in this stage seem to be more different from coarse ripple sands than the latter are from dune sands. Simons, Richardson and Albertson (1961) would not, of course, have encountered them because they used a fairly coarse medium sand in a recirculating flume. Rees (1966) has pointed out the scarcity of data on fine sands. The finest used by Gilbert (1914) had a sieve size of about 0.35 mm. The existence of a sudden change in ripple sands has been demonstrated in the present work. The change occurs (as closely as can be discerned at present) at a sieve fifty percentile for Population A of 0.25 mm. During the investigation, coarser sands were clean and devoid of argillaceous matter, contained little Population B, the sieve sorting of their Population A's showed a strong correlation with grainsize and their ripples were high in relation to wave lengths. Finer sands were often rich in argillaceous (including clayey) matter, were rich in Population B, the sieve sorting of their Population A's did not appear to depend on grainsize and the ripples were small and low in proportion to their wave lengths.

Kalinske and Hsia (1945) reported obtaining ripples in silt. Asymmetrical ripples in coarse silt are a familiar sight to geologists. Bagnold (1955) demonstrated that bed load sedimentation was physically possible in laminar flow. Rees (1966) experimented with very fine, but clay free, material ninety percent of which had diameters between 0.006 and 0.018 mm. He obtained ripples of similar appearance to the fine ripple sand structures produced in the present investigation. In Rees' experiments, the grains in the bed must have been entirely within the laminar sublayer. In fact, the whole flow was laminar during the early stages of the runs but probably became turbulent as a consequence of ripple formation. Rees associated ripple formation with the availability of suspended material above the bed. In the present work the existence of much temporarily suspended material above the bed was, of course, associated with the existence of ripples. In the present investigation the finest particles found in a fine ripple sand Population A were only just over twice the diameter of the coarsest particles used by Rees.

Durand (1952, quoted in Bagnold 1966) reported the visible saltation of quartz grains faded out at a grainsize of 0.2 mm. In the present investigation, as far as could be observed, particles, finer than this but still observable, moved in the gentle, low trajectory saltation previously described but hugged the bed very closely. Sundborg (1956) concluded that, critical conditions for particle movement, particles below 0.3 mm in diameter would be enclosed in the laminar sublayer. It is tentatively suggested here that the transition from coarse to fine ripple stage sands is associated with falling grainsize allowing the bed roughness elements due to Population A particles, to become enclosed in the laminar sublayer. The sudden acceptance of more fine interstitial material by the bed may, perhaps, be associated with its concentration near the bed because of the absence of flow components, in the very close proximity of the bed, to carry such matter back upwards and away from the bed. It is further suggested that the acceptance of cohesive matter into the bed renders the sediment, as a whole, cohesive and must make the vertical force required to lift Population A grains from the bed become highly variable because of variations in cohesion associated with their several solid-solid contacts. Under such conditions, Population A sorting would be expected to be variable and often poor. A large amount of clay would probably stop the Population A mechanism altogether.

<u>Coarse ripple stage</u>. Population A's of the coarse ripple

stage evidently occur with fifty percentiles between 0.25 and 0.9 mm but those coarser than 0.7 mm appear to be rare. These Population A's show strong evidence of packing selection during deposition. Their sieve sorting is apparently predictable from a knowledge of grainsize. Selectivity of grains becomes rapidly worse with increasing grainsize and the fade-out and disappearance of these Population A's seems to be associated with this effect. Optimum development of these Population A's seems to be achieved with little bed load turnover. Some evidence suggests that very slow bed load movement favours this. Movement of grains seems to take place only when velocity maxima occur near the bed. It is thought that, during growth of these Population A's, the grain crests project beyond the laminar sublayer into turbulent flow. This effect doubtless increases with grainsize. It seems possible that these suites of grains may follow some packing law which becomes increasingly difficult to obey as turbulence affects the bed. Within their common size range (0.25 to 0.6 mm) coarse Population A's always seem to differentiate first, the formative process being able to concentrate suitable grains from the flow by factors of two or three.

Dune Stage. Dune stage Population A's apparently have a fifty percentile size range running from about 0.25 mm to at least 2.2 mm. Much coarser ones may possibly exist.

For coarse sands the stage commences at the critical stage for particle motion but for finer ones it succeeds the ripple stage. Evidence suggests that hydraulic influences are important in the selection of dune stage Population A's, selectivity apparently becoming better with increasing grainsize. Evidence suggests that more bed load turnover is required to achieve optimum sorting than is necessary in the ripple stage. Dune stage Population A's appear to have a coarse to fine differentiation sequence with distance of travel like that of coarse ripple sands. Possibly these Population A's represent a stage wherein the influence of the laminar sublayer has become negligible and particle motion has not become sufficiently intense to allow rheologic bed load motion. The strong influence of settling velocity may be due to the comparatively rapid sedimentation burying newly deposited grains too rapidly to allow packing influences to exert a significant effect. Also, a large proportion of deposition takes place on foreset slopes where the removal of unsuitably packed grains may not be readily achievable.

Rheologic stage. Whether or not a series of Population A suites coincides with plane bed, standing sand waves and antidunes is not known. It is suspected that all the flume examples and most of the natural ones represent conditions not far from the transition to rheologic bed load transportation.

The size range of rheologic Population A fifty percentiles is known to range from 0.17 mm to 4.75 mm. No evidence exists that either figure is near a limit. Probably the fine ripple stage has a direct transition to the rheologic stage. Particle motion during this stage has not been reliably observed. The sieve-measured size range of these Population A's is almost constant whereas the gradient sorting is variable. Particle differentiation during this stage is less strong than in the ripple and dune stages, possibly because Populations B and C are more quantitatively important and the overall composition of sediments can approach that of the bed load. Rheologic Population A's can accumulate between closely packed pebbles. Some sediments in this stage apparently contain two Population A's. Probably the finer one, in the cases studied, forms a greater proportion of the sediment than the coarser one. Tentatively it is suggested that, during the deposition of the finer Population A, rolled grains may jam on the bed in the manner suggested by Moss (1963) for traction clog formation. Perhaps the flow of the rheologic mass may sometimes be strong enough to lift such particles over each other so that, locally within the fine Population A, a coarser one can be formed. The fine Population A, the evidence suggests, would be able to grow through the interstices of the coarse one. Unfortunately time has not permitted detailed investigation of these sediments.

Bagnold (1966) thought that momentum transfer from grain to grain is of dominant importance in the transfer of kinetic energy in the rheologic bed load. As previously suggested, packing is probably very important because, in such an environment, unstably placed grains projecting from the bed could be readily removed. Hence, perhaps, the consistency of sieve sorting measures.

Laminae. Laminae occur throughout the range of Population A's studied. They are physical entities so the arbitrary thickness limit of McKee and Weir (1953) will not be followed. Details of sedimentary structures are rendered observable by visual contrasts between the laminae making them. Bed load laminae are each characterised by a Population A and the sharp junctions between adjacent laminae are due to abrupt changes from one Population A to another, coarser or finer, during deposition (Moss 1963).

Traditionally, laminae have been attributed to flow fluctuations. Kuenen (1966) suggested that this explanation was offered because no reasonable alternative was available. Jopling (1966) noted that well defined bedded structure could develop in an essentially steady state of flow and sediment transport. Kuenen (1966) reasoned that, if fluctuations caused laminae, then laminal changes should be ten to a hundred times as frequent as they actually are. Moss (1963) suggested that, because of packing requirements and the strong influence of grains already on the bed and built into a Population A on the selection of new grains, a growing Population A would not tolerate change. Thus a Population A brings about its own end by making only a limited selection of grains from the passing bed load until there are too few of them left to maintain its further growth. Another Population A, coarser or finer and consisting of grains now more readily available in the bed load is then seeded and a new lamina starts to form. Kuenen (1966) also suggested that a "like seeks like" principle acted during the formation of a lamina. He disagreed with Moss that saltation could be responsible but did not have a glass-sided flume and, consequently, could not view particle motion from the side. Many published descriptions of saltation seem to imply violent motion and omit to mention that the same forces that lift the grain from the bed also decelerate it as it approaches the bed once more.

Bed load laminae occur on sea beaches where they can be several centimetres thick and can extend up to 25 feet in lateral extent (Thompson, 1937). They are laid by breaking waves which, from the present viewpoint, represent fluctuations that dwarf any in rivers or flumes. Basumallick (1966) performed granulometric analyses on samples of successive laminae making fluviatile foresets. He found little sign of modal change laterally within laminae and thought there were signs of rhythmic deposition when sequences of laminae were studied. His Figure 10 (p.53) shows a section through sequences of laminae some of which abruptly wedge out against each other laterally as well as having sharp sequential junctions.

The present work only reinforces my view (Moss, 1963) that it is the exacting selection of Population A grains and the fact that a Population A, by virtue of packing phenomena, refuses to accept gradual change, that causes bed load lamination.

Crystal growth analogy. Although knowledge of both phenomena is far from complete, the analogy between what is known of growth on a crystal face and growth of Population A is rather striking. In the former case, it may be presumed that ions or molecules approach the face under the influence of attractive forces but are usually repelled by other forces unless they are of the right type, approach the right site and, in the case of molecules, probably approach in the right orientation. Population A grains are attracted towards the bed by gravitational force but, unless they are of a suitable size and shape and arrive at a suitable spot on the bed in a favourable orientation, they are repelled by fluid dynamic lift. Probably the two phenomena are fundamentally related in terms of force fields.

Population B.

The results of the present work suggest that, in my earlier study (Moss, 1962, 1963) inadequate attention was paid to the finer grains of Population B and that, whereas the general nature of this population was elucidated, more detailed work would have been rewarding in revealing the strong environmental response of this suite of grains.

Population B (Moss, 1963) is a population of particles that occurs interstitially to Population A. If Population C is present Population B doubtless fills in spaces between its particles and Population A particles as well. The abundance of Population B is limited by the amount of pore space between larger grains. Consequently, unless Population C is abundant, Population B is always inferior in quantity to the associated Population A. In general, Population B must coincide with the so called "matrix" of a sandstone. The upper size limit of Population B is set by Population A or, more specifically, the size of the pore spaces between the Population A grains. Because the Population A grains act as a sort of sieve mesh, the largest Population B grains are invariably highly elongated. The lower size limit of Population B, where such exists, is set by hydraulic forces at the bed-flow interface. It is apparent from the present work that both bed load and suspended load can contribute particles to Population B. During the flume runs, the actual formation of Population B was not observed directly but the nature of sediments formed on the bed make it obvious that this population is formed contemporaneously with Population A. Fine ripple stage sands, for example, always had a grey colour due to interstitial argillaceous matter while actually forming.

Population A is evidently diagnostic of bed load sedimentation. Population B diagnoses bed load sediments of unidirectional currents. It is absent from wave-laid sands on open beaches. Population B is environmentally sensitive and is best described in terms of the stage sequence.

Fine ripple stage. In the fine ripple stage, Population B varies in quantity but can be abundant, almost filling the Population A interstices. Its size range is great and it often includes clay particles. As already mentioned, it is thought that, because the laminar sublayer encloses the bed surface, fine particles cannot be lifted back into the flow by turbulence, once they closely approach the bed. Thus they can become concentrated and some may pass down into the interstices between the larger particles.

Coarse ripple stage. In the coarse ripple stage Population B is poorly developed and normally makes only a fraction of one percent to a few percent of a sediment. Its size range is usually very small, ranging from just smaller than the associated Population A particles and stopping inside the sand range. Often even fine sand is quite absent. As a result of this, coarse ripple stage sands are often very clean. The phenomenon causing the rejection of most of the otherwise suitable potential Population B grains was clearly observable during the flume runs. A fluid dynamic lift barrier returns them to the flow and they are often sent into temporary suspension. This barrier becomes effective when the Population A fifty percentile exceeds 0.25 mm. The effect of this barrier must, it is felt, be regarded in terms of probability because of the effect of turbulence near the bed. The current may, momentarily, have a very low velocity especially on foreset slopes. If feed was added to the flume, a cloud of fine material would pass downcurrent and visibly affect the composition of the laminae as it passed, an unusually large amount of fine material entering the bed. However, the frequent turnover of material building ripples must rapidly reduce the amount of fine material and Population B must be rapidly reduced unless there is a large influx from upstream. Possibly, the natural materials used in the investigation represent an extreme because virtually no ripple stage sedimentation takes place in the channels of the local streams during floods when the water is turbid and, during low stages when the ripple stage usually occurs, flowing water passes almost entirely over bed load deposits of the previous flood. Consequently, comparatively little argillaceous matter is available to the flow. On the other hand, it must be stressed that muddy fine ripple sands and clean coarse ripple sands were frequently observed to occur virtually side by side in the same flow.

Dune Stage. Population B in the dune stage is too like that in the coarse ripple stage to warrant separate description. Much the same situation seems to prevail and the only difference noted was that the suite of particles tended to have, in general, a slightly better developed fine tail in the dune stage sands. Flume run 2E dramatically showed the efficiency of the mechanism keeping fine material out of the bed. It will be recalled that, beneath rheologic bed load, a minute dune foreset formed and a sample from it contained virtually no material less than 0.1 mm in diameter. A level bedded sand from nearby on the bed (that is, a rheologic bed load sand) contained 24% material less than 0.1 mm in diameter.

Rheologic Stage. At first thought, it may seem odd that well developed fine tails in sands characterised only the deposits of the weakest and strongest currents encountered during the investigation. However, it must be accepted that the rheologic bed load, although caused to exist by the current, creates its own internal environment, has its own physical relationship with the bed and acts as a sort of buffer zone between flow and bed.

Population B is generally much more abundant in rheologic bed load sediments than in coarse ripple stage or dune stage deposits. Because it is interstitial to both Populations A and C it can sometimes even exceed Population A in abundance if the sediment is dominated by Population C.

Its size range can be great and, in both natural and artificial deposits, argillaceous matter is always present. Size distributions of natural rheologic stage Population B's show a very marked tendency to split into two parts. The bulk of the Population B is usually made of particles a little smaller than the smallest grains of the associated Population A. These coarser Population B fractions show a marked tendency to become less abundant with decreasing grainsize. The finer portion of Population B shows a very much smaller tendency to become less abundant with falling grainsize and forms a "tail" running into silt and even clay grades. The artificial rheologic Population B's showed this apparent tendency to consist of two parts less markedly.

The elongation function curves of Population B have consistent characteristics. Feature 2 can, with little doubt, be assigned to contributions from both Population A and Population B. The evidence suggests that the largest grains of Population B are usually extremely elongated and that comparatively large, elongated Population B grains are much more common than in the ripple and dune stages. It is thought that the larger particles are virtually sprayed into the mesh made by the Population A grains as a result of collisions with larger grains. Feature 1 evidently occurs entirely within Population B. It is a minimum in the elongation function curve caused by a paucity of elongated grains. This paucity is due to some feature of sedimentation, not of source material. It seems highly significant that feature 1 is coincident with the abrupt slope change of the sieve cumulative curve that occurs where the two apparently different parts of the Population B size distribution join.

There can be no doubt that fine material, of the same size as the suspended load above, is present in the rheologic bed load. That its presence could affect the viscosity of the moving mass has already been envisaged. Whether it exists in the same proportion as it does in the water above is not known and how freely it is exchanged with similar material in the water above is not known either. For present purposes it can be reliably reasoned that, ideally, particles with settling velocities above a certain value will occur in the rheologic mass only but particles with settling velocities below this value will be distributed throughout the flow and the rheologic bed load. Temporary suspension may reduce the abruptness of this transition but, because the depth of a flooded river may be of the order of a hundred times as great as the thickness of the rheologic bed load the concentration of particles in the bed load is almost certain to show a marked fall in abundance over a small range of settling velocity, the concentration reduction being roughly proportional the ratio of entire depth to the bed load depth. Moreover, the elongation function curve of the bed load would show a minimum in a long dimension range over which the equant grains were all in the bed load and the inequant grains were distributed throughout the flow and hence relatively rare in the bed load.

In the light of the above considerations, the general nature of the Population B's of rheologic bed load sediments can be explained.

It seems reasonable to suppose that, beneath the rheologic bed load mass, an efficient zone of fluid dynamic lift cannot be maintained. The bed is under continuous intense bombardment by grains propelled downwards after intergranular collisions. It seems highly unlikely that such a disturbed flow pattern near the bed could form an efficient barrier to fine grains. Even if this reasoning is wrong we know that there is no efficient barrier here simply because of the abundance of Population B in the sediments. It is postulated that grains a little smaller than the forming Population A will bombard the bed surface which will act as a sieve for them, retaining those that can pass into the bed sufficiently far to avoid being removed again. By analogy with sieving, the largest of these will be markedly elongated. Under such conditions, grains of all sizes downwards from this will be packed into the bed. But there will be an inheritance of the abundance and shape distribution of particles in the rheologic bed load which, in turn, will be set by the distribution of particles between suspended load and bed load. Thus the bed load deposits will, so to speak, fingerprint the suspended load above the rheologic bed load mass.

Figure 163 shows how the processes bringing about the properties of Population B under the rheologic bed load appear to operate, in terms of size distributions and elongation function curves. The original material is supposed to have almost any size distribution and, for convenience, a horizontal elongation function curve (Figures 163A and 163B). Figure 163C shows the size distribution of the material after it is set in motion by a strong current. It is split into two fractions, one in suspension and the other comprising the rheologic bed load mass which contains a small proportion of material of the same size as that in suspension. Figure 163D shows the elongation function curves for two fractions split in a slightly different way. One is for suspended load and the other is for material of a size occurring in the bed load only. The two curves overlap in terms of the long dimension because the split is in terms of settling velocity.

Figure 163E shows the supposed size distributions of the three populations of a bed load deposit formed from the transported material. Figure 163F shows, separately, the elongation function curves for the three populations. The minimum in the Population B curve results because it represents a range of the long dimension wherein the equant grains are concentrated in large numbers in the bed load and are consequently copiously available to sediments. Elongate grains of the same long dimension range are distributed throughout the flow and are not concentrated in the rheologic bed load mass. Hence the elongation function curve reacts to a relative paucity of elongate grains and shows a minimum - feature 1. Figure 163G shows the size distribution for the sediment (obtained by summation of the size distributions of the three populations). Figure 163H shows the elongation function curve for the entire sediment (allowing for the fact that the elongate, largest Population B grains are much less common than are Population A grains of the same long dimension range). The curve, of course, has the same complex form as that of a typical rheologic bed load sediment.

In flume experiments, it was noted that, in those runs where suspended load samples were taken, feature 1 lay beneath the steeply climbing coarse end of the suspended load elongation function curve. Also feature 1, in run 3E, occurred over the same long dimension range for each sediment. In the flume runs feature 1 and the equivalent feature of the sieve cumulative curves were less well marked than in the natural deposits. This is readily explained because the very shallow flume water did not allow such large differences in concentration of fine material to exist between suspended load and rheologic bed load. The bed load occupied about a third of the depth. In a river, it would more often occupy something like a twentieth to a hundredth of the depth.

Run 1D can now be considered. If a feature 1 and a feature 2 happen to occur in the same long dimension range, they will tend to cancel each other out. They approach being mirror images of each other. Moreover, feature 2 cannot be well developed if elongated grains over its long dimension range are almost all in suspension. In such conditions this feature will be suppressed. The features of the curves of run 1D are probably suppressed for some combination of these reasons. The natural sediment No. 1230 (Figure 37) may well show this cancellation effect in its elongation function curve.

The evidence that feature 1 is, indeed, a reflection of the suspensive power of the depositing current seems exceedingly strong. For convenience, the phenomenon manifesting itself as feature 1 in elongation function curves and as a corresponding abrupt gradient change in sieve cumulative curves, will be called the "suspensive diminution". Its significance will be discussed later.

Population C

The present investigation has left no doubt that Population C consists of particles large enough to be rolled by the current over the surface created by the growing Population A. Rolling is a complex process and was discussed at length by Moss (1963). Population C, once deposited, exists in a sediment as large, often isolated particles interrupting the general framework (due to Population A). Sometimes, however, Population C particles exist in juxtaposition. Population C grains could, it was thought, come to a halt individually for differing combinations of reasons. Population C shows great variations in quantity in sediments. Often it is absent but it can reach about 80% of the whole sediment in gravels. One difficulty of investigating Population C is that one can never be sure whether the largest particles present in it are the largest that could be physically present or whether they represent the largest particles that were locally available at the time or site of deposition. Inevitably, whereas the small samples used in this study may be excellent for the study of Populations A and B, they often fall far short of perfection for studying Population C. If occurring in a dispersed state, this Population may contribute only a dozen or so grains to the sample.

Rolling grains seem to have three important characteristics that affect their behaviour and distribution. Firstly, they can roll only over surfaces of particles finer than themselves and, consequently, can be readily halted by roughness elements of their own order of size or larger, resting on, or projecting from the bed. If thus halted, they must remain, unless the current is strong enough to lift them. Secondly, as they roll, they acquire kinetic energy by virtue of both their rotation and their forward progression. The faster they move, the more kinetic energy they have available to enable them to surmount obstacles on rough bed patches. Probably, as a result of this effect, rolling grains seem to either roll over slowly once or twice before stopping again or accelerate to a speed approaching that of the near-bed current and often move considerable distances before stopping (Moss, 1963). Thirdly, rolling grains tend to move downslope as well as downcurrent and are consequently likely to become concentrated on channel bottoms and in depressions in the bed and to be sparse on steep bed slopes. This effect is particularly noticeable on foreset slopes, the larger rolled particles often reaching the base of the slope. Also, in the field, differentiation of pebbles with respect to shape was qualitatively obvious on foresets laid from rheologic bed load. The pebbles that have come to rest on the steeper parts of the foreslope are usually, on average, flatter than those that have reached the less steep lower part of the foreset.

Ripple and dune stages. In the present work it was found that, in terms of the ratio of the size of the largest Population C grains to the size of the associated Population A grains, there was actually a fall from the fine ripple stage to the coarse ripple stage and from the latter to the dune stage. Within the dune stage, there was a fall with increasing Population A particle size. Probably, this conclusion needs some qualification, factual though it is. Probably fine sands do not form dunes but stay in the ripple stage until the onset of rheologic bed load motion whereas coarse ripple sands undergo a transition to the dune stage first; it seems possible that fine ripple sands could well have coarser Population C grains because they could persist into transportation conditions of a relative strength not represented in coarser sands. Similarly, sands over 1 mm in Population A diameter do not form ripples at all, the dune stage starts as soon as the current strength is sufficient to move the bed load. Also, if ripples and dunes cover a bed, the largest particles that can be moved are likely to become buried in depressions at the upstream end of the patch and not reach areas covered by such structures farther downstream.

In view of the above considerations, it is concluded that the results for Population C may not give the full picture of this population for these conditions but it is quite clear that the rolling power of currents laying ripples and dunes is not great, the limit being particles only a few times the diameter of the associated Population A grains. Hooke (1968) reported motion of particles 2.35 mm in diameter and over sand mixture averaging 0.22 mm in diameter which was forming dunes in a small flume. The average depth was under 3 inches.

During the investigation it was noticed that Population C usually formed under about 10% of the sediment, by weight. However, some sediments show much higher proportions and, when this occurred in the flume, the Population C elongation function curve usually followed that of the parent mixture very closely. This implies lack of selectivity. The traction clog phenomenon (Moss, 1963) could, of course, occur in ripple and dune stages, one grain causing others to stop and bringing about a local concentration of halted rolled grains on the bed. Under these conditions, because of the limited size range of Population C, the finer Population C grains cannot pack into the interstices of the larger and, as a result, the proportion of Population C in ripple and dune stage equivalents of traction clogs would be expected to be relatively low. Figure 164A is a histogram of the percentages of Population C in all ripple and dune stage sands, both natural and artificial. Although data are inadequate for firm conclusions to be drawn, it does seem possible that there could be a minor second mode at around 25% Population C.

<u>Rheologic bed load stage</u>. That there is a sudden, dramatic increase in the rolling power of a current, once it has generated a rheologic bed load mass, there is no doubt. Pebbles suddenly become transportable in large numbers over

beds of medium or even fine sand. Moss (1963) suggested that the rolling of large particles such as pebbles and boulders in this stage of flow led to the formation of a special type of deposit, typified by river gravel (but probably making most natural conglomerates as well). These deposits were called traction clogs. Because one such deposit has now been made in the flume there now seems little doubt about the existence of this special depositional mechanism in which Population C take over control of the bed from Population A. Briefly, the mechanism involves pebbles and, sometimes, boulders being rolled along, while sand forms rheologic bed load, until one or more large pebbles are stopped for any one of a variety of reasons. The reason may be that some boulder may be too large for the current to move any more, a bedrock projection may halt it or the bed roughness may be locally greater so that rolling particles are slowed and stopped. Because pebbles and boulders following behind cannot leave the bed, they must be brought to a halt and a jam of pebbles and boulders will form. Evidently Populations A and B and smaller Population C particles are deposited between the large, jammed particles, smoothing the surface sufficiently for more to roll over the bed surface once more. However, because some of the larger pebbles and boulders still project above the bed, jamming is likely to repeatedly recur until a gravel deposit is formed. A more extended discussion of this process was given by

Moss (1963). Although this was necessarily somewhat speculative on the evidence then available, a great deal more evidence collected in the present study, even to the making of such a deposit, leaves little doubt that the suggestion was essentially correct.

It will be recalled that the flume gravel was produced in a current of only 67 cm/sec and in the same flow as a medium sand. The further suggestion of Moss (1963) that the strength of a current needed to remove a traction clog may be very much greater than that of the depositing current was not tested in the flume. However, inspection of the beds of the immature local streams seemed to throw some light on the problem. A typical river gravel, viewed in section as in a terrace, consists of tightly packed pebbles with their interstices filled with sand. The bed of the stream itself appears to consist, normally, of a monolayer of the coarsest pebbles or boulders available to it, packed tightly together. Little or no finer material is visible however save for discrete patches of sand often along the river margins. The pebbles and boulders often have plants growing on them and individuals can be seen to be in the same place in successive years, even after intervening floods. Removal of pebbles and boulders from the bed surface often requires considerable physical effort - several times that required to lift them if they merely rested on the bed. They are, in fact, both keyed in together and embedded, in their lower portions, in sand so that, as pointed out by Lane and Carlson (1954), it is necessary to provide sufficient force to draw water through the sand immediately surrounding the pebble, as well as enough to raise the pebble itself, in order to lift the pebble. In other words, the bed acts as a sort of hydraulic brake against the removal of the pebble, immediately the pebble tends to move. Doubtless the copious acceptance of Population B by rheologic bed load deposits and the tendency of fine particles to fill the Population A interstices, increases the efficiency of this braking mechanism.

If the pebbles and boulders forming the bed surface are removed, it is found that they do not form a deposit but, rather, a monolayer. Beneath it, almost invariably, is typical sandy river gravel in which pebbles and boulders as coarse as those making the monolayer are usually quite rare. Removal of the monolayer often causes erosion of sand and finer material from the cleared area. In one case examined the monolayer overlay sand with scattered pebbles. Also, if boulders are not common and the monolayer is built of pebbles only, imbrication can be developed to an astounding degree, the long axes of the pebbles dipping steeply upstream while their intermediate axes are at right angles to the flow.

Because some of the larger boulders in many monolayers project downwards for some distance into the underlying traction clog, the monolayer is unlikely to be an actual deposited sediment. If it were, it would have an essentially planar contact with the underlying traction clog deposit. It is axiomatic that a true lag deposit, consisting of material that a current cannot move laterally, must be a monolayer. Moreover, these monolayers are precisely what one would expect if a strong current started to erode a traction clog deposit. This circumstance will now be considered.

Suppose that a strong current, able to add to its bed load, passes over a traction clog deposit, Population A will be removed together with any interstitial Population B. Also any finer Population C grains that the current can lift over the larger ones will be transported away. However, these finer particles will be removed until their surface level drops sufficiently far for the larger Population C particles, remaining stationery, to give protection from the current. Thus, in contrast to a bed dominated by Population A, a bed dominated by coarse Population C increases its resistance to erosion as it is eroded. As the bed becomes coarser, resistance to flow increases and the particles forming the bed surface are not only large and well packed but their lower portions are embedded in sand and hence are even more difficult to move than before. Evidence suggests that the larger boulders settle down together, as all smaller particles are scoured from around them, to form the monolayer. Also, if large particles can be moved within the space between neighbouring particles but not lifted over them, an imbrication arises, each particle coming to rest in a position giving maximum resistance to the flow.

The geomorphological importance of these monolayers can only be great. At this stage, however, one can only speculate about their effects on other phenomena. Probably their importance varies with the size of the largest physically and chemically stable rock particles that can be commonly supplied to the river. The longer the largest available particles the more effective, in resisting erosion, the monolayers that can be built. The roughness provided by them causes suspension via excessive turbulence and checks the velocity of the flow. Where such layers exist, the river cannot downcut physically without first destroying the layer. This means that many streams can only cut bedrock from beneath them during extreme floods perhaps, on average, every hundred or even every thousand years. In turn, this brings some degree of stability to the valley sides for quite long periods. Furthermore, this stability lessens the supply of detritus to the river. Thus Population C and the monolayers derived from it, must act as a sort of damping mechanism on geomorphological processes. The ramifications of a severe flood, strong enough to break up the monolayers and to cut down bedrock level beneath, must be profound. It is small wonder that soil-forming processes seem often to bespeak slow chemical change punctuated by violently sudden outbursts of physical redistribution of matter.

It is of interest to compare the behaviour of pebbles in streams with that of pebbles on sea beaches composed entirely of pebbles. In the former environment the pebbles, almost invariably, belong to Population C and have their interstitial spaces packed with fine material. In the latter environment (Moss, 1962, 1963) the pebbles belong to Population A, are well sorted, and lack interstitial fine material so that water can flow rapidly between them. A pebble in a river may remain unmoved by quite a strong flood whereas quite small waves can lift one the same size bodily from the bed and the beach surface is resculptured at almost every tide.

The evidence very strongly suggests that, in the context of the quantitative assessment of bed load phenomena, not only should rheologic bed load motion be considered separately from conditions of less intense particle motion but rheologic bed load sedimentation should be treated in two ways according as to whether Population A or Population C dominates the bed surface. No existing bed load function can be applied usefully to a mountain stream, with large amounts of energy available for particle transportation, flowing swiftly over a monolayer of boulders and transporting almost no solids.

Primary Structures

Although the present work falls far short of explaining the true basic nature of primary bed load sedimentary structures, it does seem to add some factual matter which may be of eventual use in unravelling the puzzles that these phenomena present. Some highly tentative suggestions will, however, be made.

Primary bed load structures (including plane bed structures which are just as much structures, physically, as ripples or dunes) may be subdivided into those of local causation, such as current bedding formed where a stream discharges into a pool, and repetitive structures such as ripples and dunes. The former are frequently associated with local loss of bed load transporting power due to changes in channel configuration. Current bedded rheologic stage sands, associated with bed undulations caused by traction clog gravel deposition, are a familiar example. These are often well displayed in sections of river terraces. At lower transportation rates, flow separation must be important in producing local current bedding. Also in this general category are banks and bars constructed of traction clog gravels.

Ripples and dunes appear to be by far the most important repetitive bed load structures. Although often somewhat similar to initial inspection, these two structures differ in a number of ways. It is pertinent to mention some of the main known differences here.

Ripples are usually less than a foot in wavelength. Their wavelengths appear to bear an approximate relationship to the grainsize of the constituent particles, larger particles making the larger ripples. In finer ripple stage sands (and silts) the wavelength may be only one or two inches. Dunes, on the other hand, are seldom less than about 1½ feet in wavelength (save, initially, when a ripple is converted to a dune) and have a maximum wave length of, perhaps, hundreds of feet.

Ripples of the coarse ripple sand stage have a high ratio of height to wave length. For dunes, the ratio is lower. Fine ripple stage sands also usually have a lower ratio than do coarse ripple stage sands. Fine ripple stage ripples tend, almost always, to have crests that are fairly continuous, running at right angles to the general flow direction. Coarse ripple stage sands may show this property but, very frequently, the crests are discontinuous and irregular. That such irregularities may be systematic was shown by Allen (1965). Dunes (other than some very large ones that extend right across channels) appear to be usually irregular and to show few crests of much lateral continuity with respect to the current direction.

The manners in which ripples and dunes originate and develop contrast strongly. One can never be sure that one has seen ripples actually start forming. If one starts with a plane bed, over which flow conditions would allow them to form, and watches carefully, first the bed is plane then, perhaps a few minutes later, the bed is no longer plane but is covered by very low amplitude corrugations, not asymmetrical like ripples, but evidently symmetrical. Their crests lie at right angles to the flow and they form a regular pattern. They have about the same wave length as the ripples into which they will develop but their amplitude, when first observed, may be only two or three particle diameters as against a wave length of three inches of more. For convenience of description these structures will be called "protoripples". If many fossil sandstones are studied closely, some of the apparent plane laminae may sometimes be observed to be very slightly corrugated in a similar manner but it is not yet known whether some, or all, of these structures represent protoripples. The amplitude of protoripples grows with time whereas their wave length remains essentially constant. After a time, quite suddenly, and at different points on the bed, minute foresets appear on the downstream sides of the protoripples and the structures then grow into ripples. The ripples then grow to some fairly constant height, without changing their wave lengths significantly and, provided that flow and feed remain fairly constant, migrate downstream without significant further change. Very probably, the transition from protoripples to ripples is associated with a critical condition at which the growing amplitude of the protoripples causes flow separation to occur at the crests. Avalanching contributes a little to the downstream motion of particles making coarse ripple stage sands. This type of motion has not been observed in fine ripple stage sands.

Dunes arise more individually and less systematically than do ripples. They may or may not be anteceded by ripples. Dunes have not been seen to originate directly from protoripples. When dunes arise from ripples an individual ripple will suddenly grow larger and longer in relation to its height, cut off the main flow (by its flow separation) from some of the downstream ripples, and advance over them as it grows. Thus, in the transition from a rippled bed to a dune bed, only some of the ripples may seed dunes. Dunes may be articially seeded, provided that flow conditions are suitable, by merely dropping a handful of sand onto the bed. Erosion takes place on the upstream side of the resulting elevated bed patch while a foreset forms on its downstream side. Dunes also arise unexplainedly, a tiny foreset structure appearing on the bed. Possibly the return of the separated flow from an upstream dune may cause bed irregularities to form and hence seed a new dune. Dunes grow both by individual growth (mainly by adding to their foresets), and by a process of capturing downstream dunes that has already been described. Growth apparently continues until the flow depth imposes a limit to their size. In the Murrumbidgee River, active dune crests have been seen only an inch or so below the water surface. Avalanching is an important factor in the forward progression of material built into dunes.

Ripples are known to form under great depths of water in the oceans. It is not clear whether these are fine or coarse ripple sands or both. Dunes seem to be mainly characteristic of shallow water but whether or not depth actually places a physical limit on their formation is not clear. Avalanching appears to be the result of shearing that takes place when a current temporarily moves down a foreset slope. It is suggested that, the greater the depth, the more effective this phenomenon in flattening foresets. Were this true, dunes would tend to be "ironed out" in very deep water.

Both ripples and dunes are built almost entirely of Population A grains. Such grains are in a state of saltation over the bed and arrive in position from a saltatory state. The evidence is strong that fluid-dynamic lift is the important force concerned in causing this motion. For both structures, the length of a saltational jump is many times less than the structure wave length. The Population A's of the three stages under consideration have different but overlapping size ranges. Fine ripple sands (and silts) appear to run from within the silt size range to a fifty percentile of 0.25 mm. Coarse ripple sands run from 0.25 mm upwards but apparently become less common with increasing size and do not reach 1.0 mm. Dune sands start with a value of about 0.25 mm and reach at least 2.2 mm.

A rather striking feature of the deposits of the three stages is that, although all are rather alike, save for the liberal acceptance of a fine tail into the Population B of fine ripple sand stage, their Population A's show differing relationships with other parameters. Fine ripple stage sand Population A's are variable and no rational variation pattern could be found for their sorting relationships. Coarse ripple sand Population A's seem to have sorting relationships tied closely to grainsize. In the local rivers, the sorting deteriorated rapidly as sieve size increased. Dune stage Population A's seem to have their sorting closely related to settling velocity, the sorting (as closely as it could be measured in terms of settling velocity) becoming more exacting with increasing size. The present interest in these relationships is that each stage seems to be characterised by a different "sort" of Population A. Why this is so is not yet known (although some suggestions were made earlier in this thesis). But it is important to establish whether the properties of the sediments are due to the existence of the structures. The answer is, almost certainly, negative. Level bedded sediments, in these three stages, apparently differed little or not at all from those built in structure foresets. The only slight difference was that the larger potential Population C particles probably roll to the foot of foresets but Population C is a minor constituent of these deposits.

Finally, it is necessary to recall the observed apparent relationship between the existence of ripples and dunes and the temporal persistence of current direction. Apparently, the more closely the current is held rigid in direction with respect to time, the more favourable the conditions for the formation of the structures. A highly tentative, partial, qualitative explanation of these structures follows.

Suppose that a current flows over a plane bed of fine sand and that the current is just strong enough to cause bed load motion. Suppose, also, that the current direction does not vary with time. It is postulated that the resistance to flow offered by the bed does not manifest itself on the flow homogeneously, but, in a manner perhaps somewhat analogous to the generation of waves by wind on a water surface, the static bed causes the generation of small internal waves in the water and that these waves remain stationary with respect to the bed. Such waves, even if energetically small, will superpose their effect on the passing flow. It seems feasible that the superposition of the waves could divide physical conditions on the bed into a series of bands according as to whether the motion due to the wave is in the same direction as that of the current or in the reverse direction. The development of protoripples makes it seem highly likely that a wave phenomenon of this general nature does exist.

Because the flow would not be very turbulent under the conditions postulated, the bed may be considered as being divided into a series of bands. Alternate bands would be in contact with accelerating water and decelerating water. As a consequence of this, bed load motion would respond to the resulting banding of velocities (and, hence, velocity gradient) near the bed. Particles would tend to leave bands of high velocity gradient and to accumulate in bands of low velocity gradient. Thus would protoripples form in phase with the postulated waves. Once formed, the protoripples, in turn, would tend to anchor the wave pattern to the bed. After the protoripples had reached a certain amplitude, flow separation would occur and ripples would form from them, in phase with the waves. It is suggested that the waves and the ripples have a stabilising effect on each other.

Now imagine an otherwise similar situation but suppose that the current direction is temporally more variable. The waves would be more irregular in nature and, more importantly, no point on the bed would be characterised for any length of time by either accelerating or decelerating water. Consequently protoripples could not form because they would take a finite time, often minutes, to develop. Because ripples are seeded by protoripples, they will not form either and the bed will remain planar. Similarly, rapid discharge fluctuations would be expected to inhibit protoripple development but these are probably less common in nature than are temporal directional changes.

In the coarse ripple sand stage, the effect of turbulence is becoming more important and turbulence will vie with postulated waves in producing effects on the bed, tending to break up the wave pattern. The effect of near-bed turbulence will increase with both bed grain size and velocity. However, it is suggested that ripples develop from protoripples as before and that temporal consistency of current direction is necessary for ripple formation. Irregular ripples would result, possibly, from partial breaking up of the wave pattern by turbulence. As velocity or grainsize grow larger, the effect of near-bed turbulence must increasingly cancel out the effect of the waves. However, during the coarse ripple sand stage, the waves still control ripple wave length. Ripples therefore become rarer as grainsize increases, finally fading away at a grainsize of just below 1 mm. The dune stage is thought to represent the final elimination of the effect of waves by turbulence. Once the waves are removed they are no longer able to control structure wave length and the dunes continue to grow until stopped by the effect of depth. They are, of course, sensitive to temporal changes of current direction because their orientation is related to that of the current. Thus they can only develop if the current direction remains fairly consistent.

The transition to the rheologic bed load stage involves the production of a mass of grains which, en masse, behaves like a fluid. It is thought that this mass normally, in nature, tends to eliminate raised structures because it tends to flow downslope as well as downcurrent (Moss, 1963). As a result, the mass is likely to add material to itself from the upper parts of slopes and to preferentially deposit in depressions. Level or nearly level beds tend to form and these are, apparently, the most common structure laid from rheologic bed loads in nature. In flumes (Simons, Richardson and Albertson, 1961) the level bed is apparently of minor importance, standing sand waves and antidunes being the more usual bed forms. Although these structures occur in nature they are clearly many times less common.
Because they are orientated strongly to the current direction it is again suggested that temporal maintenance of current direction, such as occurs in flumes, favours their formation. In nature, temporal variations in the direction of strong currents are very important as can be readily observed in flooded rivers. It also seems likely that environments in which sand beds are in violent motion are likely to be

impersistent in time and to be likely to deepen and remove all trace of antidunes and standing sand waves that may have existed. Finally, the intimate association of such structures with surface waves suggests that they may be confined to very shallow water.

Particle Differentiation in Unidirectional Flows

For the immediate purpose of this discussion, unidirectional flows may be regarded as alluvial (entirely bedded in their own deposits) and non alluvial (wherein the flow passes partially or wholly over solid boundaries, such as bedrock, that the flow cannot immediately carry away in particulate form. Intermediate cases, of course, exist. It is traditionally stated that river deposits tend to become finer downstream. This statement is, of course, generally correct. The objection to such a statement is that it is pantechnicon, covering some variety of processes all of which should really warrant separate attention.

That detritus continues to evolve after being initially set in motion from its source area there is no doubt. The larger particles are subjected to significant abrasion and breakage and many particle types are attacked chemically while in alluvial deposits. Most physical fragmentation processes tend to become less effective with falling grainsize. A discussion of such effects was given by the author (Moss, 1966) with particular reference to quartz particles. The properties of a fresh sediment must depend on the physical evolution of detritus, as controlled by the nature of weathering rocks, any modifications to particles of the detritus that has taken place since initial weathering, fractionation of particles by dynamic sorting processes prior to their arrival at the site of deposition and, lastly, the fractionation that is associated with the actual laying of the sediment at its site of deposition. This last fractionation functions also as some part of the penultimate fractionation of those mentioned for all sediments that will form downstream afterwards. The laying of a sediment must alter the composition of the stream load and this alteration will affect downstream sedimentation.

The first major physical differentiation that takes place as unsorted detritus is fed to a stream is the separation of material into bed load and suspended load. Over medium sand or coarser material in bed load motion, silt and clay are held in suspension and often even repelled from the bed by fluid-dynamic lift. Strong flows can hold fine sand and coarser material in suspension. This differentiation is, of course, well known. The important relevant features of material in turbulent suspension are that most flows are well able to transport all suitably sized material supplied to them and that such material travels at the speed of the current. In young streams, lacking flood plains, almost all suspended load is passed directly downstream. A very small proportion is deposited where valley configuration causes turbulence damping during floods and another small proportion enters bed load deposits. The bed roughness caused by traction clog deposits (gravels) and their capping monolayers stimulates turbulence and hence suspension. In alluvial streams supplied with sand, or sand and pebbles, the channel size and shape are manifestations of a complex equilibrium between bed load and flow. An important result of this equilibrium is that sufficient turbulent suspensive power is generated as a result of it, even at low flow stages, to maintain most argillaceous matter in suspension. The suspension is therefore due, not just to the flow but, perhaps just as much, albeit indirectly, to the coarser material of the bed load. The frequent association of fine, often rippled, sand with argillaceous matter in an intimately interbedded manner, both in modern and ancient deposits, and the fact that the interstices of such fine sands are often filled with argillaceous matter, suggest that fine sands are less effective than are medium sands and coarser bed load materials in promoting the suspension of argillaceous matter. Alluvial rivers, of course, deposit argillaceous material as overbank deposits during floods. However, because the thickness of these deposits is limited by water depth and because, as the river meanders, it undercuts or removes these deposits, in general this environment acts as a mere transit camp for argillaceous material.

In young streams the characteristic pebble or boulder monolayer, lining the bed, in addition to causing downcutting to be very discontinuous, seem to cause channels to be wide and shallow. This effect evidently causes all sand and finer material to be transported downstream, the grains often spending much time in temporary suspension. Sand below the monolayer is, of course, protected from immediate erosion. The traction clog mechanism must concentrate pebbles and boulders in the upper reaches of streams and excess finer material, beyond that which is interstitial to them or is deposited in protected areas between gravel bars, is passed on downstream.

Rivers supplied only with sand or those that have deposited their pebbles farther upstream, seem to be able to bring about major differentiation largely through the formative process of Population A. Whereas the evidence suggests that major bed load differentiation does not take place to any great extent when rheologic bed load sands form, largely because of the liberal acceptance of Populations B and C, the dune and coarse ripple sand stages achieve major particle fractionation in the bed load. This seems to arise because, firstly, Population A's are made by concentration of the coarsest commonly available particles. Secondly, once formed, the Population A forming the bed surface rejects almost all finer particles from the bed surface. Thirdly, if dunes or ripples form, temporary suspension of these rejected grains hastens their passage downstream.

It follows from the preceding reasoning that the fining of material downstream in a river is not a simple case of fine material outrunning coarse. It is far more accurate to say that the coarsest material commonly available reacts with the flow, by one of several mechanisms, in such a way as to hasten the transportation of all finer material downstream. Thus, evidently, exists a sort of grainsize hierarchy, particles of any one size being passed downstream relatively rapidly, often by a series of mechanisms, until they become the largest particles commonly present in the stream. At first, the "ruling" grainsize will be in Population C and derived lag monolayers. Farther downstream it will be in Population A. In descending order, the grainsize classes must take their turn in making the bulk of the bed load deposits, forming their own equilibrium with the flow. When this happens, their transportation rate drops greatly. The bed load deposits of a river, then, consist of a series of bands moving very slowly seawards, each dominated by particles of a particular grainsize, finer than those upstream and coarser than those downstream. Any two of the dominant grains in a river deposit may have weathered out in the headwater region of the river at very different times.

If one adds to this picture the complexity of storage capacity in the flood plain of an alluvial river, each dominant grainsize tends to be stored in great quantities. This, of course, slows the average transportation rate of the dominant grainsize enormously and the seaward migration of the bands, for large rivers, must become very slow indeed, even by geological standards.

In marine environments, the situation must be more complex. The author (Moss, 1963) has previously suggested a mechanism by which particles of small size ranges come to dominate large littoral areas. The mechanism suggested was closely analogous to that now suggested for the fall in grainsize down the courses of rivers but, of course, over a period of time, marine transportation must follow a pattern that is less linear than transportation in a river. However, it seems reasonable to expect that the same principles would be broadly obeyed where offshore currents operate.

Some Possible Effects of Depth Variation

Colby (1961) reviewed the effect of depth variation in alluvial flows. No single simple relationship between depth and other parameters appeared to exist. In the present work, it has been concluded that fluid dynamic lift, at least in the ripple and dune stages, is the important fluid force affecting the bed load particles. This being so, the velocity gradient just above the bed would be more important than the actual depth.

The purpose of this part of the discussion is to deal with depth in a rather different sense, concentrating attention on the manner in which depth variations may affect the relationships between particles being moved in different ways by the current and also on any possible resulting manifestations of depth variation on sediment formation.

Each solid transportation mechanism operated in a zone within the flow. Each zone reaches the bed and, consequently, the zones overlap. Rolling (and sliding) particles occupy the thinnest zone, one particle thick, on the bed. Evidence suggests that, for rolling to be efficient, the concentration of such particles must be low. Otherwise traction clogging will halt them or, if the current is strong enough, they will pass into saltation. The next zone is that of saltation. This may be only a few particle diameters thick or, possibly, very much thicker when rheologic under strong currents. Particles in temporary suspension cannot, in an absolute way, be distinguished from grains in normal saltation. The one named phenomenon grades into the other but, over dunes in the flume, temporarily suspended load often reached the surface a foot or so above the bed. Solids in turbulent suspension are, of course, distributed throughout the flow.

Evidently, this overlapping stratification can exist in quite shallow water but a stage must be reached, as depth decreases, wherein the pushing down of the more vertically extensive loads must begin to affect bed load sedimentation. It seems reasonable to assume that, if water is deep, then the load in turbulent suspension, for a given feed to a river, will be relatively dilute in the region of bed load sedimentation, but, if the flow is shallow, the suspended load will be more concentrated in this zone and more will be available to enter bed load sediments. In this way, depth variations would be expected to manifest themselves in bed load sediments particularly in the fine tail of the Population B of rheologic bed load sands and gravels. Unfortunately, the general muddiness of the water is also affected by the composition of the feed to the flow.

It is very evident that water only a tenth of an inch thick can have considerable transporting power. This effect can be a nuisance when one is draining a flume after a run. But as water approaches such small depth, zonation of transported solids approaches an impossibility. Suspended load cannot separate from bed load, temporary suspension cannot take place, upward vertical components of turbulence must diminish in importance, saltatory leaps must be greatly curtailed, and capillary forces associated with the water surface must become more important. It is in soil formation that very shallow water is, perhaps, most important. It would be very surprising if one or more of the effects mentioned above did not manifest itself, in some detectable manner, in the deposits of thin veneers of flowing water. A search for such possible effects appears to be warranted.

In alluvial rivers, major depth changes, over short distances, are uncommon. Material in turbulent or temporary suspension returning to a sand bed in motion must, almost invariably, continue to move as bed load after arriving on the bed. This is because, if a current is strong enough to maintain particles of a certain size in suspension, it is also easily able to move them as bed load. In the time it takes such particles to move from near the water surface to the bed it is extremely unlikely that the current will have lost enough velocity to be unable to move them as bed load.

Suppose that a strong current carrying fine sand and argillaceous matter in turbulent suspension could be brought to an abrupt halt. The material would immediately settle to the bed, the coarsest fraction completely settling out of the now static water first, then the next and so on. Thus a graded layer would form on the bed. The upward grading, because grains of each size would have different distances to settle to the bed, would be best assessed in terms of the last appearance, in the graded layer, of particles of differing settling velocities. Such a model is, of course, energetically impossible, but it does represent a sort of theoretical end member of a series of possible situations, the other end member being the situation normally pertaining in a river. Between these two extremes, the important criterion deciding the nature of the forming bed is whether or not the current on the bed is still strong enough to move all the returning suspended grains along the bed, if only for very short distances, and of redepositing them. If the current can do this, Population A and hence bed load deposits, will form. If it cannot, then the suspended material will form a suspended load deposit directly.

The ideal situation for the balance of deposition to swing towards the direct deposition of sand sized material appears to be when a strong unidirectional current with suspended load, enters some form of deep basin of essentially static water and much deeper and wider than the unidirectional current. The water surface slope is almost lost and the flow is retarded by turbulent mixing with surrounding static water. It is not the mode of origin of the strong current that matters, as far as sedimentation is concerned, but the change in physical conditions just above the bed that occurs horizontally between the last point at which a particle was held continuously in turbulent suspension and the point at which the particle arrives back at the bed-flow interface.

The most likely combination of deposits on the bed will be graded laminae and fine ripple stage sand, with or without actual ripples (for it is now known that ripples may or may not actually form). The deposit would be interbedded according as to whether the balance of relevant parameters allowed returning particles to be moved as bed load or not before final deposition. The next most likely combination would be coarse ripple stage sands (if a significant proportion of the suspended load exceeded 0.25 mm in diameter), fine ripple sand and graded beds. Dune stage sands would be less likely to be involved because they evidently consist only of fairly coarse sand. The association of bed load deposits and directly returned suspended load would be expected to be set in a fine suspended load deposit - mud.

The varved clays of glacial lakes have long been interpreted in terms of the waning of currents (rivers) as they enter lakes and the resulting gradational deposition evidently results from the damping of turbulence. Such deposits usually involve material finer than sand. Bouma (1962) and many later workers have described a sequence involving graded sand laminae, ungraded sand laminae and ripples, interbedded with finer deposits, from the stratigraphic column and from the modern sea floor. Detailed consideration of such deposits is outside the scope of the present study. Also, there is little point in speculating further about these sediments at a time when it should be possible, by applying techniques, such as those employed in the present study, directly to the problem. That sequences of this general nature could form on the sea floor, off the mouths of rivers during major floods, seems entirely reasonable to the author. Perhaps there is no need to invoke some special mechanism such as turbidity currents to explain all sediment associations of this general type.

An interesting analogy to the topic under general discussion occurs in the levee deposits of some strong-flowing alluvial rivers. Intimate interlaying of suspended load and fine bed load deposits, doubtless representing returned suspended load brought into bed load motion, are very common. The latter frequently show ripple marks. Graded bedding has, apparently, not been observed however. The reason for this may be that this returning suspended load is arriving on the bed in a steady state situation, as turbulence falls laterally from the main flow, rather than because of a temporal sudden change in the flow. It would be interesting to find out if some of the sandy matter in levee deposits lacks Population A. If it does, it may represent undisturbed returned suspended load.

APPLICATIONS, COMMENTS AND SOME POSSIBLE DEVELOPMENTS

This section involves some discussion of topics peripheral to the main theme of the project and describes applications of the results, both real and conjuctural.

Bed Load Sedimentation, Living Organisms and Fossilization

Organic activity can be very high or very low just above, on, and just below a water-sediment interface. Knowledge of sediments as substrates for organic matter was reviewed by Purdy (1964). More specifically, he cited work by Sanders (1956, 1958) in which a correlation was found between the proportion of deposit feeders in the infauna and the proportion of silt and clay in the bottom sediments. The nature of sedimentation and sediments is only one of many factors deciding the overall intensity of organic metabolism taking place in the bed vicinity. Also, sedimentation is involved in the preservation of fossils by providing the matrix in which they come to rest. It now seems possible to gain a more exact idea than heretofore as to the physical nature of conditions under which some past sediments formed and hence of the physical conditions under which fossils found in the sediments may have lived. The following brief remarks represent an outline attempt to apply some of the findings of the present study to these subjects. Without doubt, the subject warrants a special project.

The mere existence of bed load sediments must, almost invariably, mean an adequate supply of oxygen. It is also axiomatic that, the greater the rate of vertical accretion of sediments, the more dilute the record that will be left behind by a given general rate of organic metabolism. Light cannot penetrate into bed load sediments more than a few grain diameters. Consequently it is probable that the amount of organic material passively arriving in the sediment during sedimentation is an important ecological factor.

Fine ripple stage

When fine ripple stage sands are laid the current strength is very low, usually around a few inches per second. Moreover, there is probably not always need for a small organism to move against the current in order to maintain a position with respect to the bed. Below the separation zone of ripples and just ahead of the foresets, occur zones of very low current velocity. The physical environment is unsuitable for sessile forms because either erosion or sedimentation is taking place all over the bed. However, mobile forms or organisms that can burrow will be able to compensate for the relatively slow bed changes.

The fact that the bed accepts clayey matter means that it will also accept small sized food material during sedimentation. Because food will be trapped in the bed during actual sedimentation, a suitable environment for many burrowing forms, notably actual deposit feeders, must exist. Also, if ripples exist, coarser organic debris is likely to be trapped in the troughs where it may become buried under ripples to make a second food source. Again, more food material will be sent into temporary suspension above the separation zone thus providing a food source for near-bed nektonic forms. Fine ripple stage deposits must, by their nature, invite bioturbation. It seems doubtful whether planktonic larvae, unless able to move about immediately on landing or to survive temporary burial, could develop on an active bed in the fine ripple stage.

As regards fossil preservation, it seems highly significant that the composition of fine ripple stage sands approaches that of a self-bonding moulding sand. Population B, abundant and often including some clayey matter, imparts these properties to the sand. Thus the sand is able to make detailed casts of objects, the resolution of the casting being related to the grainsize of the finest particles commonly present in Population B. Any potential macrofossil resting on the bed and not buoyed by gases will be very unlikely to be washed away because the current will be weak. Also, because the ripples advance a wave length or so in a matter of a few minutes to a few hours burial is likely to take place before remains can be scavenged or destroyed by bacteria. Hence, this is a physical environment in which macrofossils are relatively likely to be buried even before their soft parts are destroyed. Not only this, but the sediment is more suitable than most for taking casts of fossils, including, in this case, soft parts. (On clay or mud surfaces, it seems likely to the author that most soft-bodied macrofossils would be likely to be destroyed organically before burial because of the normally very slow rate of sedimentation.)

Figures 165 and 166 show a specimen of sandstone from Ediacara, South Australia. The specimen (A.N.U. No. 17892) shows two casts that appear to belong to the late Precambrian medusoid, <u>Ediacara</u> (Glaessner and Wade, 1966). The lithology and general sedimentology of rocks containing these and many other soft fossil preservations were described by Goldring and Curnow (1967). These workers recorded that ripple marks, asymmetrical and symmetrical, were very common in the rocks preserving the fossils. The specimen does not precisely represent the ideal case deduced here for the preservation of macrofossil soft part impressions, but is sufficiently close to warrant consideration. Most of the specimen consists of asymmetrical ripples in coarse clean sand but the fossils are preserved along the base of this obviously coarse ripple stage sand at its junction with a fine, dirty, silty sand. The fossil detail is actually recorded by the finer material. Analogy to the results of the present work is striking, more particularly to run 2A in the flume. In this run coarse ripple stage sands formed and sent finer sand into temporary suspension. The finer sand landed on the bed downstream to make dirty, fine ripple stage sands over which the coarse ripples advanced. That something very like this physical situation aided in the preservation of the medusoids shown in the specimen seems highly probable.

Fine ripple stage sands often have leaves and other plant debris in their troughs and fossil specimens often contain casts of similar materials. This association occurs probably for reasons already given. Pollens and spores could be expected to occur in these sands because of the general acceptance of fine material.

The general impression given by fossil fine ripple stage sands is that they are often associated with rich faunal assemblages and that, even if fossils have been dissolved from them, detailed moulds are often preserved. If the foregoing reasoning is somewhere near to being correct, it may not be mere coincidence that major finds of evidently soft-bodied macrofossils have been found associated with ripples in the Precambrian of South Australia. Perhaps it would pay dividends if some concentration of search for Precambrian fossils in general were to be directed on beds in the fine ripple sand stage.

Coarse ripple stage

The coarse ripple stage differs from the fine ripple stage, in the context of the present discussion, mainly by virtue of fluid-dynamic lift and near-bed turbulence achieving considerable ability to repel fine material from the active bed. This means that, by comparison, very little fine organic food material will be able to pass from flow to bed during sedimentation. Thus, although vertical accretion of sediment may still be slow, there appears to be less reason for burrowing organisms to forage in these sands. The physical environment appears to favour fairly fast moving nekton and organisms that can rest on, or partially in, the bed and take advantage of the concentration of fine food particles which must be moving with the current a little above the bed. Truly sessile forms could not, of course, flourish. Although coarse ripple stage sands probably have the same potential for rapid interment of macrofossils without removal by the current, they have less cohesion and their casting potential is less when compared with fine ripple stage sands. Pollen and spores and other small microfossils would be expected to be relatively rare in coarse ripple stage sands because of repulsion from the bed by fluid-dynamic lift. In consequence, they could, perhaps, be expected to be relatively concentrated in any associated fine ripple stage sands. It seems extremely improbable that planktonic larvae could settle onto an active bed in the coarse ripple stage.

Dune stage

The dune stage represents, in the present context, a further development of conditions that set in with the coarse ripple stage. The currents will be stronger and, in general, both erosion and sedimentation will be relatively rapid. Fluid-dynamic lift and near-bed turbulence are still very effective in keeping fine material from the bed. Thus fine food material will be rare in the bed during sedimentation. Burrowing organisms will need to burrow rapidly but there will, in general, be little food supply beneath the bed surface. A food-rich zone will move above the upstream slopes and the return bed current, after separation, will bring some of it back to the quiet area ahead of the foreslopes. Only creatures capable of moving relatively fast will be able to take advantage of this because the advancing foreset, alternately by accretion and avalanching, would bury any sessile organism, perhaps under twenty feet or more of sand. Because a food supply is kept moving above the bed, fast moving nekton will have a food supply. (In the Murrumbidgee, young fish are commonly seen feeding near the bed, often in large numbers, just ahead of the dune foreslopes.) It is very doubtful if planktonic larvae could land on the active bed and there would appear to be little point in their doing so.

In the dune stage, the general evidence suggests that the lighter, thin shelled remains of potential macrofossils could probably be moved. Usually they would be interred at the foot of a foreslope. The flow would be adequate to move a newly dead organism, of specific gravity near that of water, out of the dune environment. Because the sand is coarse and noncohesive with no fine matrix, it will have little casting power and, probably, if shells were dissolved from within these sands, the sand would collapse into the resulting vacuity.

A look at the results for fossil current bedded sands published by Moss (1962), in the light of newly acquired knowledge, suggests that a large proportion of these may belong to the dune stage. In general, and small wonder, current bedded sands are amongst the worst sediments for yielding organic remains. Often they occur, virtually barren, between richly fossiliferous other beds, but, for all we know, the water above and around the active dunes could have swarmed with life.

Rheologic bed load stage

Before proceeding with a consideration of the ecological implications of transportation and deposition by rheologic bed loads, it is necessary to recognise the frequently intermittent nature of bed load sedimentation. Unidirectional currents flow in response to disequilibrium and tend to restore equilibrium. Thus, unless some other effect takes place (such as rain on mountains from which a river flows) to maintain the disequilibrium, any current by flowing, will remove the cause of its existence and consequently wane. Thus a section through bed load sediments will usually represent only a series of separated time periods, the remaining time representing either periods of formation for sediments that were later removed, periods of erosion and periods when the current was too weak to bring about either erosion or sedimentation. Bed load sediments may thus be frequently left exposed on the bed, presenting the same surface on the bottom for long periods. The bed could thus support life in an environment that had little to do with the physical conditions under which it had formed. It seems reasonable to suppose that the more violent the flow stage the more intermittent the sedimentation and the shorter the bursts of sedimentation. It is in the light of these considerations that rheologic bed load sediments can perhaps be best examined.

While working with the flume and watching rheologic bed load motion from the side the impression was gained that, within the actual mass, few organisms could function for any length of time. The concentration of sand was so great, rates of erosion and sedimentation were so high and the speed at which the whole mass moved was so fast that it would be difficult for an organism to maintain a position relative to the bed. Even if, say, a pelecyopod could maintain its position, it probably would not be able to open its valves without having its whole internal cavity crammed full of sand in a second or so. Moreover, if pebbles are in motion, structural damage to any fixed organism would be very likely to occur.

Because the bed accepts fine material, down to clay size, it will probably also accept fine organic debris and hence have the same food potential as fine ripple stage sands. As already noted, the bed-flow interface (or, more strictly the bed-rheologic bed load interface) is not likely to be a generally inhabitable environment. Above the rheologic bed load layer, of course, a food supply will be distributed through the flow due to strong turbulence but water will often be highly turbid. Only very fast-swimming nekton will be able to maintain a position above the bed. To live in such an environment, organisms must need to be able to burrow, preferably rapidly, into the bed below the zone of bed load motion or to be able to swim swiftly above it.

Bed areas over which rheologic bed load motion, due to unidirectional currents is normal and continuous, are probably rare. Flooded rivers may maintain sand in this state for fairly long periods and, in some littoral areas and estuaries affected by high amplitude tides, this motion is probably fairly normal. The swash zone of beaches is of interest in this context. The usual equilibrium on sandy sea beaches involves the sand being in rheologic bed load motion. Physically, this is a rather special environment, Population B being typically quite absent (Moss, 1962). However, this absence probably results from a gradual winnowing away of fine material from the environment rather than an almost absolute rejection of fine material such as occurs in the dune and coarse ripple sand stages. Work by Friedman (1967) also suggests that this may be so for he reports fine tails in beach sands laid in localities where fine material is readily available such as new river mouths. In view of this and the evidence produced in the present work, it seems reasonable to suggest that, when rheologic bed load flows over the swash zone (and the rheologic mass is readily visible under the backwash), organic matter will be added to the bed. Also, along a beach, the life-rich surface water of the sea comes in contact with the bed and the wave action ensures virtually continuous replenishment of organic matter. That a whole variety of fast-burrowing forms live below the bed in this zone there is no doubt.

As mentioned in a previous section, rheologic bed load deposits with coarse Population C build traction clog deposits and the resulting resistance of such deposits to erosion brings about bed stability and hence extreme sedimentological intermittency. The upstream reaches of many rivers seem to exemplify the organic ramifications of these physical processes. The bed may remain stable for many years between occurrences of floods capable of significantly disturbing it. Moreover, around and under the pebbles and boulders, occur microenvironments in which life can exist without having to experience the rigours of the main current. Boulders become coated with sessile plant life and often sport long fronds trailing in the current. When a major flood sets the bed in motion, the whole environment is destroyed and probably, much of the fauna and flora with it. After the flood has passed, the stream bed must be recolonised. There will often be time for many generations of most of the species before the next act of destruction. After such floods the near-channel overbank deposits of some rivers are often seen to be rich in finely fragmented clam shell.

In marine environments, analogous bed conditions, between major storms, evidently provide an excellent environment for sessile forms. In fossil sediments, broken and damaged shells and what appear to be traction clog deposits but with damaged shells doubling for pebbles, must often bespeak a burst of rheologic bed load transportation in an area where it did not normally occur.

Because of the presence of argillaceous matter, rheologic bed load sediments will have the ability to take casts of fossils but, of course, a medusoid or similar creature could not rest on the bed during sedimentation.

Small microfossils could be expected to occur in such deposits however, even in gravels and conglomerates. In the flume experiments, the strong resemblance, to initial inspection, between fine ripple stage sands and fine rheologic stage sands was most striking. Possibly, in the future, one of the best ways of distinguishing between the two, in the field, will be by looking at the way in which macrofossils are preserved in them.

Applications; Real, Probable and Possible

During the investigation it was necessary to concentrate attention on the more central topics concerned in bed load sedimentation. Inevitably, as the work progressed, numerous possible research side avenues and extensions presented themselves but could not be pursued because of lack of time.

General Application

Provided that a sediment can be disaggregated, its particles can be measured and, if the material proves to fall into the general category of bed load sediments investigated here, much can be deduced about the environment of formation of the material. Because the results are correlated with the occurrence of recognisable structures and other features such as the presence of pebbles, the actual measuring work on an association of sediments could often be reserved for key samples, used as checks, the general picture of sedimentation being built up by anchoring field observation to the studied samples. In some cases, there would be no need to apply the techniques at all. Obviously, for instance, fine sand showing asymmetrical ripple marks formed in the fine ripple sand stage.

Large Objects in Sediments

One very probably useful application of the techniques concerns the occurrence of pebbles and boulders in sandy matrices. If the sand, in which a pebble or a boulder reposes, can be shown to have been laid by rheologic bed load then, unless the object is very large, it is probable that the water current that laid the sand could have moved the object into position. If, however, a large pebble or boulder occurs within a ripple stage or dune stage sand then the object must have been emplaced by agents other than the flowing water. The most obvious application of this principle is as an aid in the recognition of beds to which debris was added from floating ice. In archaeological application, if, say, a stone hand axe were found in rheologic bed load sand then the object would probably have been emplaced by the current. The find would mean that there was human occupation at some point upstream at some time prior to the laying of the sediment. On the other hand, were the hand axe found within a ripple or dune stage sand then, almost certainly, there must have been human activity in the immediate vicinity at the time the sediment was laid.

Suspensive Diminution

Time has not permitted a comprehensive investigation of the phenomenon that has been called the suspensive diminution. However, there seems to be little doubt that feature 1 of elongation function curves and the corresponding feature shown by sieve size distribution must give a measure of the suspensive power of the current in terms of the size of the largest particles that can be held in essentially continuous turbulent suspension. Also a general relationship between the concentration of suspended load and the amount of Population B, finer than the suspensive diminution size, could be expected to exist. It could be possible, eventually, by studying the past deposits of a river, to assess its past maximum suspensive power and hence the flooding potential.

Somd Common Sedimentological Techniques

The present work has shed some light on the general reliability and meaning of the results produced by some of the standard techniques used in sedimentology. Almost all techniques are affected by sampling and the importance of taking samples from within individual laminae has been already discussed. All forms of granulometric analysis would benefit if all samples were thus derived. The most difficult sampling to carry out would be for the purpose of studying such problems as the change of sphericity with distance of transportation. Sphericity, as measured, very closely approximates the reciprocal of the elongation function. Consequently, the quantity must be highly sensitive to local sorting effects. Particles of the same sieve size may be in coarse Population A (low sphericity), associated with feature 2 (sphericity tending to lose a bimodal distribution) or in feature 1 (grains of low sphericity almost lacking) in different sediments in the same locality. Probably very few published studies of sphericity variation can be taken as reliably reflecting a single simple trend of any physical parameter.

Inspection of the cumulative curves presented in the present work suggests that a reasonable estimate of the fifty percentile of Population A could usually be made by mere inspection of the cumulative curve. That this point on a cumulative curve is a better reference point for statistical measures than arbitrarily chosen points, there can be little doubt. Probably some improvement in environmental discrimination would come about if statistical parameters could be related to this point.

The only practical application of the results of the main investigation that time has so far allowed is to the problem of the mode of origin of certain gravels outcropping at the northern end of Lake George, a slightly saline shallow lake centring its own discrete drainage basin some twenty miles northeast of Canberra, A.C.T.

Figure 167 shows the general locality of Lake George and the location of the gravel outcrop. The lake is fed by several small streams but periodically dries up for periods of years (Jennings, Noakes and Burton, 1964). The gravel surface lies several feet above the highest levels reached by the lake waters in recent times (from 1820). The outcrop form of the gravel deposit is reminiscent of the shape of wave-laid gravel bars, such as occur in many coastal localities. It has been interpreted as a bar formed at the edge of the lake (Jennings, Noakes and Burton, 1964). Galloway (1967), who also thought the deposits to be lake-laid, dated associated carbonaceous material at 15,100 ± 300 years B.P. An alternative interpretation is that the gravel deposit is fluviatile (Garretty, 1939), that Lake George represents a tectonically lowered portion of the course of a former river and that, possibly, the outcrop form was later sculptured by lake waves.

Marine wave laid gravels are readily recognizable (Moss, 1962, 1963), consisting of essentially pure Population A. In the present study, fluviatile gravels have been characterised in detail. The two types of deposit are very different. However, before proceeding with a description of the results of granulometric studies some salient field features will be briefly described. An exposure of the gravel deposit shows some fifteen feet of sedimentation units, some consisting of sandy gravel, some of level bedded sands and some of current bedded sands with foresets usually dipping steeply northwards away from the lake. Figure 168 shows a typical section of the deposits. Many of the sand units contain scattered pebbles and almost all are well laminated. Sand laminae marginal to lakes, of course, typically dip at small angles towards the lake. These steeply dipping laminae dip northwards, away from the lake and, from their position, could only have been on its northern or north-western shore, not its southern shore. A river, on the other hand, could only have flowed northwards or southwards through the valley because of closeness of high ground to the east and west of the lake basin. Even without granulometric analysis and from field observations alone, it would seem very surprising were these deposits not of a northward flowing river. They have all the field characteristics of the bed load deposits of strong unidirectional currents.

Figure 169A shows the elongation function curve of No. 1238, a modern sandy deposit from the lake margin. The deposit, like other wave deposits, lacks Population B. It contains a little Population C. Also plotted in Figure 169A is the curve for No. 1239, a sample from one of the few sets of laminae that could be found in the fossil deposit that were dipping towards the lake at a low angle.

However, the curve is the typical curve of a dune stage sand (it is too coarse to be a coarse ripple stage sand). Probably, therefore, No. 1239 represents a dune lamina dipping upstream at a low angle as do dune topsets.

Figure 169 shows the curve of No. 1128, an open-work gravel, a type of material encountered in a previous study by the author (Moss, 1962) but not studied in the present work. Deposits of this type are relatively rare in most fluviatile sequences. Figure 171 shows the cumulative curve of the deposits. Its Population A fifty percentile has a value near 4 mm. Although twice as coarse as the coarsest known dune stage sand studied, this deposit more closely resembles dune deposits than any others investigated.

Figure 170A shows the elongation function curve of No. 1139, a sandy gravel. The curve is that of a traction clog gravel. The rise in the range p = 17 - 26 mm appeared to be due to the increasing dominance of elongate metamorphic pebbles with increasing size. This feature is shown by the gravel from the modern Molonglo River which could well be draining the same area as the supposed past stream. (See elongation function curve for No. 1160 in Fig. 38). Features 2 and 3 are well developed. Insufficient fine grains were measured to allow resolution of feature 1. The corresponding sieve cumulative curve (Figure 171) is a typical traction clog cumulative curve.

Figures 170B and C and Figure 172 show the results for three sands from the deposits. Of these, No. 1132 is a typical rheologic bed load sand and the other two are, apparently, double sediments. Sufficient fine material to allow accurate resolution of feature 1 was not measured.

These sediments are clearly those of a strong northward flowing unidirectional current, capable of moving coarse material in rheologic bed load. It maintained its character long enough to lay a sequence of these deposits at least fifteen feet thick. Such a current could hardly have been operative at this point unless able to pass out of the basin in a northerly direction. The evidence that these are river deposits seems strong.

Palaeothermometry

Finally, it has long been the view of the author that, because the viscosity of water varies considerably with temperature (approximately through a factor of two in the temperature range of common natural flows) and because of the several processes that lead to the formation of bed load sediments, that a possibility exists that temperature may be recorded in some way by a sediment as it is laid. Should this be so and if the temperature could be determined by a relatively simple technique, because of the ubiquity of bed load deposits, a very valuable tool would be available to earth scientists.

It will be recalled that the transition from the fine ripple sand stage to the coarse ripple sand stage, at the level of approximation that time permitted in the present investigation, was found to take place at a Population A fifty percentile of 0.25 mm. Moreover, the transition was interpreted as being associated with the ratio of Population A grainsize to the thickness of the laminar sublayer. It seems at least worth testing the hypothesis that the laminar sublayer would be likely to be thicker in colder (more viscous) water, all else being equal. Possibly, therefore, the transition from fine to coarse ripple stages would take place at a slightly coarser Population A grainsize in cold water than in warm water. It is recognised that certain other factors such as the effect of clay on apparent viscosity, overall shape characteristics of particle suites, depth, salinity, the proportion of Population C and the fact that the ripple stages persist over some range of hydraulic conditions may give rise to difficulties. In spite of this, the benefits of success in this field would be such that, even if the chances that the technique could be satisfactorily developed may seem rather small, some preliminary investigations appear to be justifiable.

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