Title

A NEW APPROACH TO HEAVY MINERAL SIZE DISTRIBUTION

by R. V. Longe

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R. V. Longe

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

The size distribution of heavy minerals in water-laid sediments has previously been explained in terms of the same fluvial sorting which controlled the grain size of the light minerals. What appeared to be a sympathetic variation between the size of heavy minerals and that of the light mineral with which they were associated led to the formulation of the concept of Hydraulic Equivalence and to belief in the constancy of the hydraulic ratio.

Analysis of over three hundred sediment samples from streams in the vicinity of kimberlite pipes in Mali indicated that neither the quantity nor the size distribution of heavy minerals depended on the size distribution of light minerals. The concept of Hydraulic Equivalence was evidently inapplicable in this situation. The facts can be explained effectively by considering the heavy mineral population in terms of three sub populations: (1) the "lag" sizes which are unmoved, (2) the "drag" sizes which are transported and concentrated, and (3) the "drift" sizes which are usually absent because they are readily swept away. The drag sizes form the bulk of most heavy mineral samples. They are transported only slowly and they are concentrated at depth in the same way as lag sizes.

It appears to be local availability alone that controls

the heavy mineral size distribution. Availability at any one point in the stream depends on what has been transported to that point. Heavy mineral size distribution tends therefore to be constant along the course of a stream except where it is modified by tributary sediment or where a change in the rock type alters the local heavy mineral availability. This leads to the possibility of long range detection of ore bodies by analysis of the size fraction peculiar to the tributary.

The theory proposed in this paper can also account for data which has been used to justify the theory of Hydraulic Equivalence.

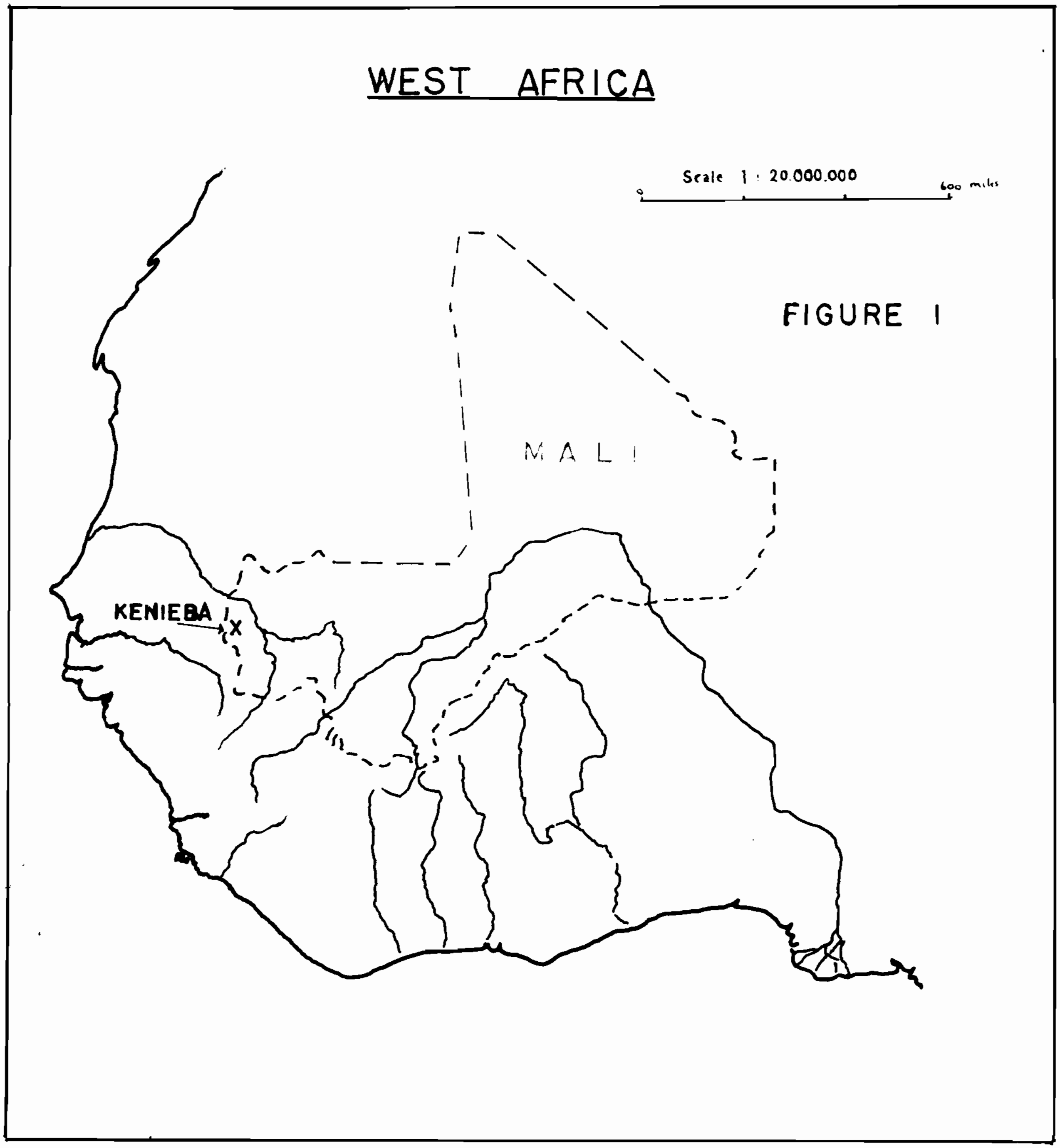
INTRODUCTION

This paper is in the nature of a progress report on an investigation, part academic, part economic, into the size distribution of heavy minerals in sediments. Far from complete, the investigation is at a stage when more questions have been uncovered than answers found.

It began with the search for a method of finding kimberlite pipes in West Africa. The coastal drainage there (Figure 1) poses few problems for alluvial prospecting. The streams are degrading and comparatively large grains of heavy minerals (+1 mm.) are transported. As rocks producing ilmenite of this size are rare there is little difficulty in trailing kimberlitic minerals to their source.

Inland, however, the situation is more complicated. The streams have aggraded under the influence of a more humid climate than that prevailing now. Since then they have continued to flow above their lowest level of degradation, following a meandering course and appearing incompetent to transport anything but the finest sediment. (Figure 30 and Addendum 6)

Under these conditions not only is the provenance of larger minerals in doubt but the problem of identifying the great numbers of very small minerals which are definitely transported becomes a major difficulty. It is a rare rock which produces a


WEST AFRICA
Scale 1 : 20.000.000
0
600 miles
FIGURE I
MALI
KENIEBA
X

heavy mineral of over 1 mm. but almost any rock yields grains of ¼ mm.

There are essentially two situations in alluvial prospecting for kimberlite pipes. On reconnaissance work a single grain of a kimberlitic mineral is all-significant because it indicates the presence of a kimberlite field. Once the field has been found the investigation develops into the search for individual pipes. For this, hundreds of mineral grains may be meaningless as they can only indicate the presence of kimberlite in the vicinity, a fact which is already known. Such a situation in Mali prompted the search for indications of the proximity of kimberlite pipes. First attempts to find a solution involved using the light mineral grain size to correct for heavy mineral sorting. But it was not until the realization that heavy minerals followed a law of their own that any progress in the investigation was made.

The size distributions of samples were determined in the field. As panning was never completely effective in separating all quartz from the finer sizes of heavy mineral it was necessary to estimate the percentage of light minerals in each size fraction of a sample. One of the objects of laboratory work has been to analyze more accurately a set of samples that had already been analyzed in the field and to justify thereby the field analysis. In the field, separation with a gold pan was followed by volume measurement in a graduated cylinder with visual estimation of heavy mineral percentage. In the laboratory, mechanical panning with a Hauetain Superpanner was followed by weighing. The field analysis appears to have been adequate as the two size distributions are comparable. (Figure 13)

The other object of laboratory work was to determine by magnetic or chemical analysis the reason for an interesting change in the mean grain size at the confluence of two rivers. A series of samples taken at 200 metre intervals along the length of a stream showed, in accordance with theory, a remarkably constant heavy mineral mean grain size. At a confluence with a stream draining a kimberlite pipe, however, there was a marked reduction in grain size. The results of X-ray spectrometer analysis showed that the change could be attributed to the tributary but it was not possible to prove that the heavy minerals from the tributary were kimberlitic.

Laboratory work has therefore provided confirmation of the factual basis of the theory without providing conclusive evidence for or against the possibility of using it as a long range stream prospecting method.

A statistical approach has not been used in the interpretation of sample data first, because the differences between lag, drag and drift sizes are evident without it, and second, because too many assumptions (for calculations of the significance of mean grain size fluctuations, for instance), would be necessary.

Later in the investigation when more is understood, and when samples are taken from an area about which more is known, a statistical approach will be much more applicable.

ACKNOWLEDGEMENTS

I would like to thank those who have helped at all stages of this investigation.

The field work was done while I was in the employ of Selection Trust Limited. For permission to use the samples and data from maps and plans I am indebted to Doctor E.R. Gerryts whose help and encouragement has been invaluable. I am also indebted for many discussions with Mr. H.J.E. Haggard whose own work has led him to an outstanding knowledge of fluvial processes, particularly in Africa.

The preparation of this thesis and the laboratory work have been under the kind surveillance of Dr. E.W. Mountjoy whose constructive criticism has been most helpful. I am also grateful to Dr. J.A. Elson for guidance where I have ventured on to the surface of geomorphology, to Professor Salman for use of the superpanner, to Dr. G.R. Webber for help with the techniques of X-ray analysis, to Mr. F. Roy for reading the final draft, and to many others who have helped in the field, in the laboratory and in the realm of ideas.

PREVIOUS WORK

It has long been recognized that heavy minerals are present in most sediments as minor constituents and that they are usually smaller than the light minerals forming the bulk of the sediment. Mackie in 1923 appears to have been the first to discuss the reason for this relationship. Since then it has been generally accepted that the disparity in size between light and heavy is because a heavy mineral is as easily transported by water or wind as a slightly larger light mineral.

This theory was first put in quantitative terms by Rubey in 1933. He defined "hydraulic equivalent size" as that size of spherical quartz grain with a settling velocity similar to the heavy mineral of size and density in question. From this premise and using Stokes' Law he went on to calculate the magnetite and tourmaline size distributions that one would expect to find within a certain quartz sand. His results are summarized in Figure 2 below.

Rubey (1933) recognized the complications of the processes of transportation and sedimentation and the difficulty of explaining them mathematically but he overcame these problems with one assumption:

> "The only assumption involved here is that, whatever the conditions may have been which permitted the deposition of quartz grains of a certain size, these

conditions would also permit the deposition of magnetite grains that had the same settling velocity." (p.5)

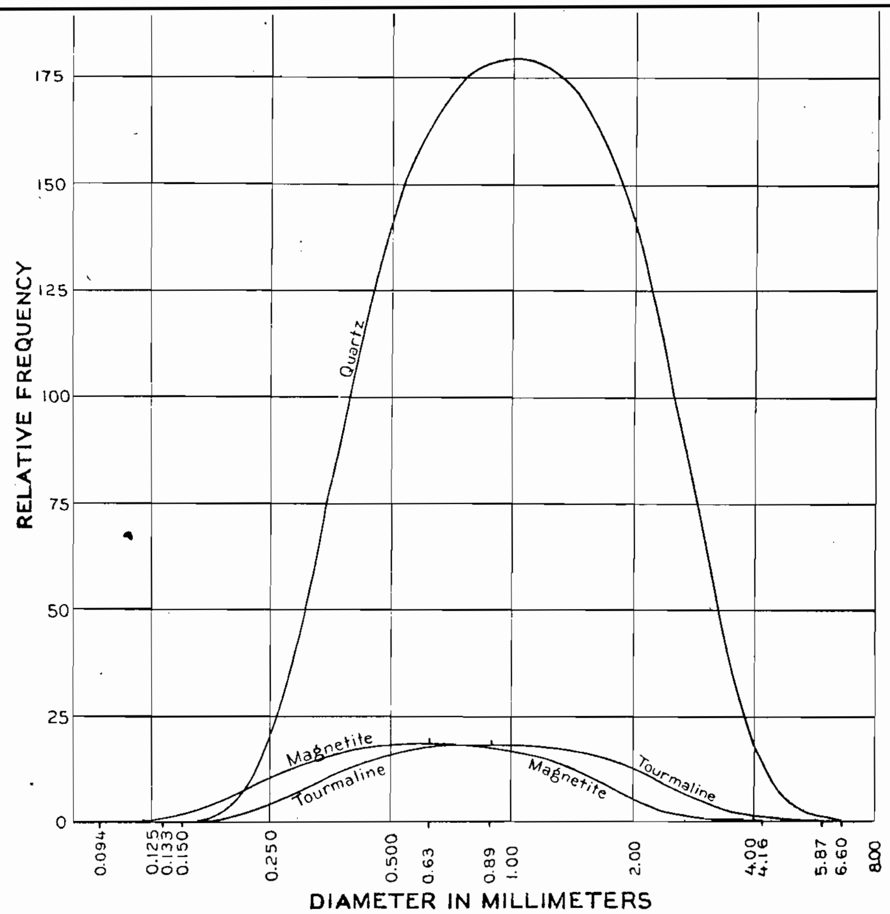


Fig. 1. Complete size-distribution or frequency curve of quartz, tourmaline, and magnetite grains within a well-sorted sandstone, according to Stokes' law.

FIGURE 2

(Rubey, 1933)

In 1935 Cogan wrote to justify on empirical grounds the use of heavy minerals in correlation.

In this respect it is interesting to note that whenever heavy minerals have been successfully used in correlation most of the uncertainties about heavy mineral transport have been by-passed through using the ratio of one heavy mineral to another instead of heavy to light.

Russel (1937) concluded, differently, that heavy minerals were preferentially concentrated in the finer-sized sediments. These were recovered by trawling the bed of a stream from a boat. He says:

> "Minerals which commonly occur as grains smaller than the average, like the accessory minerals of crystalline rocks, in addition to being more abundant in the finer portions of individual samples make up a larger percentage of samples of smaller average grain size. It is obvious, therefore, that a progressive decrease in the grain size of sediments introduced a factor tending toward an increase in the percentage of those minerals smaller than the average. The importance of this effect has not been determined however." (p.1313)

In accounts of heavy mineral sampling little mention is usually made of the type of sample. Otto in 1938 introduced the concept of the "sedimentation unit" as: "... that thickness of sediment which was deposited under essentially constant physical conditions." (p.575)

He points out the advantages and disadvantages of sampling one lamellæ or sedimentation unit. Group sampling eliminates the random variation that would occur from sampling single lamellæ but, on the other hand, sampling of too many at a time could conceal evidence of fluctuations that might be significant. The concept of the sedimentation unit is useful but it is important to realize that there may be no separable thickness of sediment, all grain sizes of which were deposited under the same physical conditions. More recent work (Moss 1962) has emphasised the number of different populations that form a sediment.

After measuring the heavy mineral content of a series of samples from beach sands, Krumbein and Rassmussen (1941) deduced that the sampling error involved was as much as 10%. They suggested accordingly that four samples should be taken at each sample position. It is appropriate to reflect at this point on how much "error" is due to sampling, how much to natural variation, and to what extent the apparent error would be altered by sampling fewer sedimentary lamellae.

In 1943 Rittenhouse, in one of the most important papers written on the sbject, confirmed the usefulness of the concept of Hydraulic Equivalence (Rubey 1933) but he made the reservation that certain "unknown factors" also contributed to the control of heavy mineral size distributions. Rittenhouses's samples were a series of twelve 2 inch cores, 40 inches long taken in a line across a river. Evidently the significance of the sedimentation unit (Otto 1938) was ignored. Not only would such samples tend to indicate a bulk composition by the averaging of many short-term variations but grouping of mid-stream with lateral samples would fail to take account of local contribution.

In 1944 Rittenhouse and Thorp, published the results of some laboratory work on the same subject. Quotations summarize their conclusions on the two main aspects of heavy mineral studies: the relation, first, of size distribution and, second, of quantity to the grain size of the sediment.

> "In natural fluvial deposits, the size distributions of heavy minerals are known to vary systematically with the size distribution of the lighter minerals with which they are associated." (p.524)

and

> "Because two samples may have the same size distribution but may carry different absolute amounts of heavies, the weight of the heavies in any particular size grade cannot be determined from the number distribution." (p. 525)

(Here "number distribution" is assumed to be synonymous with "size distribution".)

They concluded that for those minerals being transported by a stream, the denser the grains the more likely they are to be transported deeper in the water, nearer the stream bed. Conversely, for those that are less dense, preponderance in the deeper water is less marked.

Wurtz (1949) experimented in a laboratory tank with heavy minerals and sand. The object was to confirm field observations on the logarithmic frequency of placer deposits with distance along a stream. During the course of the work he noticed that heavy mineral concentration occurred at the same time and place as scouring:

> "A small concentration of heavy minerals seems to appear even before the actual appearance of the scour, i.e., the latter cannot yet be seen but its effects are beginning to show."

> "The coming of the scour is generally foretold by the appearance of a preliminary leeward deposit of heavy minerals (.....) growing more and more numerous. In fact, very minute particles of sand have already been carried away by that time." (p.198)

Later, a study of turbulence led Sundborg (1956) to conclude that only when the sediment grain size was greater than 6 to 8 mm. did the turbulence disturb the water between one grain and the next on the stream bed. Under these conditions the heavy minerals were moved with the light. When the grains were smaller than 6 to 8 mm. the turbulence did not disturb the water in the grain interstices, and the light were skimmed off leaving the heavy behind. This appears to have been the first mention of granular interaction in the formation of heavy mineral concentrations.

Sundborg ascribes heavy mineral concentration to two processes:

1. "...material enriched in the truncated erosion surface."
2. "...grains deposited in the troughs."

These statements prompt many questions: What erosion surface? Is not any erosion surface truncated? What troughs, and how is any type of grain preferentially concentrated in them?

Rogers and Dawson (1958) pointed out that the size distribution of heavy minerals in one many-cycled sandstone was the same as in the igneous rock from which the heavy minerals were derived. They concluded that the hydraulic sorting of heavy

FIGURE 3

CUMULATIVE CURVES SHOWING SORTING OF TRANSPORTED HEAVY MINERALS RELATIVE TO THOSE IN SOURCE ROCK

(for explanation see text)

Fig. 3a (after Doeglas, 1946)

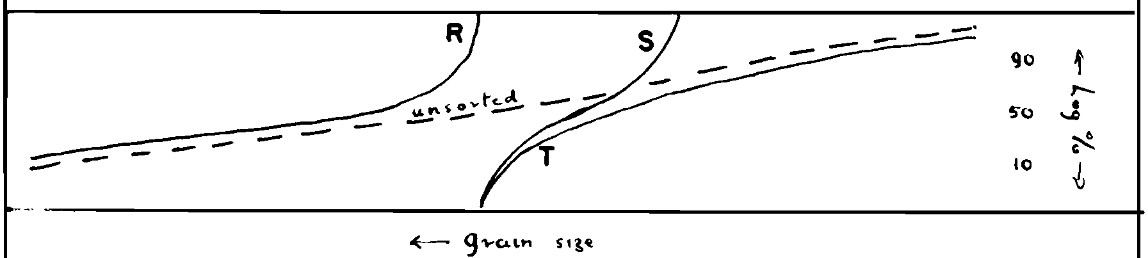
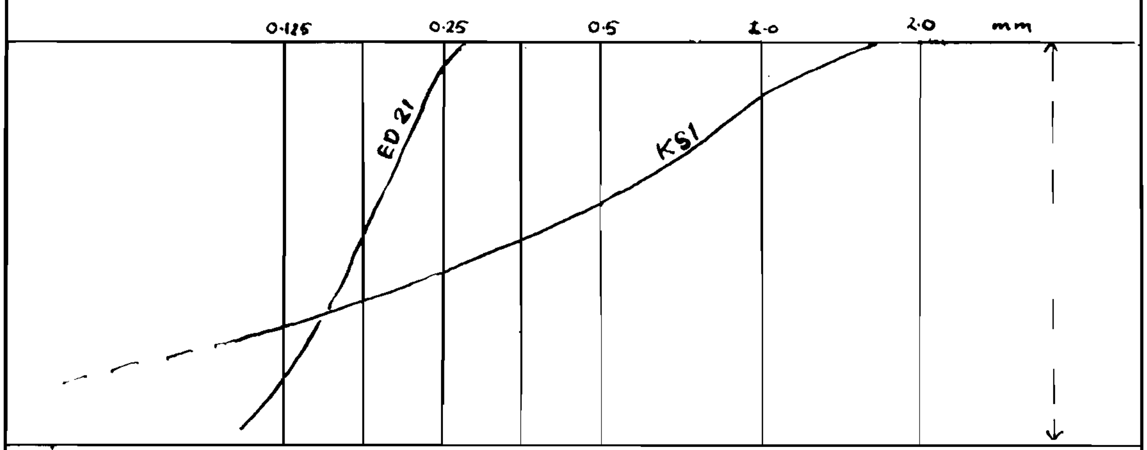


Fig. 3b (Kenieba samples)



KS 1 Heavy mineral sample from kimberlite
ED 21 " " " stream draining kimberlite

minerals was not important. Nevertheless hydraulic sorting evidently effected the mean of the distribution of the light minerals, for the size distribution in the stream sediments was not the same as in the rocks from which they were derived. In explanation they suggested: "Possibly transportational agents have no effect on the shapes of distribution curves, although they certainly influence the medians of the distributions." (p. 364)

This opinion, if applied to sediments in general as they appear to intend, is effectively refuted by Doeglas (1946) in a paper on the hydraulic control of sedimentary size distributions. He argues that an unsorted sediment subjected to fluvial sorting becomes separated into a residual (R) fraction, (Figure 3) a readily transported fraction (T), and an intermediate (S) fraction which becomes deposited at the edges of the stream channel.

McEwan, Fessenden and Rogers (1959) found more evidence in favour of the importance of the original source distribution in the subsequent sedimentary distribution. They noticed that chemical decay of granite produced a deposit with grain sizes corresponding to Rosin's law of crushing and they deduced: "This same distribution is also found in samples which have travelled several hundred yards down a small intermittent stream." (P. 477)

They concluded that the only role of hydraulic sorting is to remove the finer sizes. No mention was made of what the effect of selective transport would be on a sediment in which the coarsest grains were too heavy for the stream to move.

The validity of using the hydraulic equivalence concept to explain the quantity and size distribution of heavy minerals was first challenged by McIntyre in 1959. He investigated a beach in which there were alternating layers of light and heavy minerals. According to Rubey and Rittenhouse the size distribution of the different minerals would show sympathetic variations. McIntyre found that for five different minerals on this beach the size distributions did not correlate. He attributed this lack of correlation first to the vagaries of sampling and, second, to the possibility that: "...hydraulic conditions operate differently upon mineral grains." (p. 289)

Whatever the reason it is abundantly clear that hydraulic equivalence alone is inadequate. It breaks down completely when for instance: "...two layers which have the same quartz size distribution in mean size and sorting may have heavy minerals which differ significantly in mean size and sorting..." (p.292)

In a paper, which made many contributions to the understanding of sediment transport and deposition, Moss (1962) devoted a section to heavy mineral concentration. Perhaps one of the reasons for the significance of Moss's paper is his discussion in terms of the basic principles of mechanics. Concepts like hydraulic equivalence and hydraulic ratio encourage thinking in terms of such ideas. Under these conditions the fundamentals behind the concepts themselves go uninvestigated and undisputed.

Besides showing that simple sands are the product of three sedimentary populations, Moss pointed out the role of intergranular reaction in the formation of beds rich in heavy minerals. The stability of a grain on the bed of a stream depends on the shape and size of its neighbours. A grain surrounded by much larger grains is less likely to be moved by the current than one surrounded by smaller grains and projecting above them. Heavy minerals are found in the smaller fraction of the sediment. A heavy mineral grain tends therefore to contribute to the instability of a quartz grain next to it on the bed of the stream. Such a situation increases the probability of its replacement with another grain and so on until, ultimately, only heavy minerals remain. Moss's approach provides a convincing explanation of deposits which consist almost entirely of heavy minerals, a situation that would be hard to explain in terms of hydraulic equivalence.

Tanner (1962) produced evidence for the increased concentration of heavy minerals with depth. He noticed that the heavy mineral concentration on beaches in the Golf Coast was less than what was predicted by calculations based on the rate at which rivers supplied these minerals. He argued that the apparent shortage of heavies is unlikely to be due to dispersal either along the beach or out to sea. There remained the possibility that they were more abundant at depth than at the surface where all the samples were taken. In another paper Tanner, with Muller and Bates, (1961) goes so far as to predict that appreciable reserves of economic minerals might be discovered by drilling.

In summary: while the preponderance of heavy minerals in the finer size grades of a sediment surprised no-one, the causes of the quantitative relationships both among the heavy minerals themselves and with the light minerals in which they are found puzzled investigators. Rubey introduced in 1933 the concept of hydraulic equivalence based on Stoke's Law and this concept was developed in the 1940's by Rittenhouse and his co-authors. Because hydraulic considerations alone did not explain all the observed relationships these authors were forced to postulate other influences or "unknown factors". Since then many workers have assumed that calculations based on Stokes' law go a long way towards explaining the quantitative relationships of heavy minerals in sediments, but there is mounting evidence that hydraulic equivalence falls short of providing even a partial explanation. Russel (1957) showed that in one case, at least, the heavy minerals were most abundant not only in the finer grades of a sediment but in the finer sediments themselves. Otto (1958) directed attention to the importance of the sedimentation unit but this seems to have been ignored probably for practical reasons. In a study on turbulence and sediment transport, Sundborg (1956) explained heavy mineral concentration in terms of granular interaction. Moss (1962) in a more detailed study also used grain interaction but differently. Krumbein (1941), Rogers (1958) and McEwan (1959) have all indicated the similarity of the size distribution of heavy minerals in sediments to that in the source rock from which they are derived. Finally McIntyre (1959) demonstrated in one case, at least (a lacustrine flat), that hydraulic equivalence does not explain the relation of the size distributions of heavy minerals to that of the light minerals with which they are found.

OBSERVATIONS ON THE SAMPLE AREA

The samples were collected in the vicinity of Kenieba, a small village in Eastern Mali near the Senegal border. (Figure 1)

The dominant physical feature of the region is a 1000 foot scarp extending for 30 miles to the south of Kenieba and 40 to the north. Outliers, some of them over ten miles away, indicate that the escarpment is not a fault line but that it has reached its present position by retreating eastwards. (Figure 4) The low country to the west consists of steeply-dipping Precambrian shales. The escarpment itself is formed by flat-lying Ordivician sandstones lying unconformably on the Precambrian. Kimberlite pipes outcropping east of the scarp were probably extruded on to an erosion surface which was essentially the same in Cretaceous times as it is now. Little, therefore, of these pipes can have been destroyed by erosion. In contrast, the upper 1000 feet of pipes to the west of the cliff, but not far from it, have almost certainly been removed during the eastward retreat of the scarp.

The rivers east of the Faleme are slow and meandering. Their gradients are slight and they retain water in stagnant pools well into the dry season. Yet despite these indications of a mature drainage these rivers are eroding bedrock in places and most of the river bed is covered with coarse to medium gravel.

Two characteristics of the geomorphological history of the region have had an important effect on the heavy mineral size distributions. One is that kimberlitic minerals have been

CROSS SECTION SHOWING RELATION
BETWEEN
KIMBERLITE INTRUSIONS and EROSION SURFACES
NEAR KENIEBA

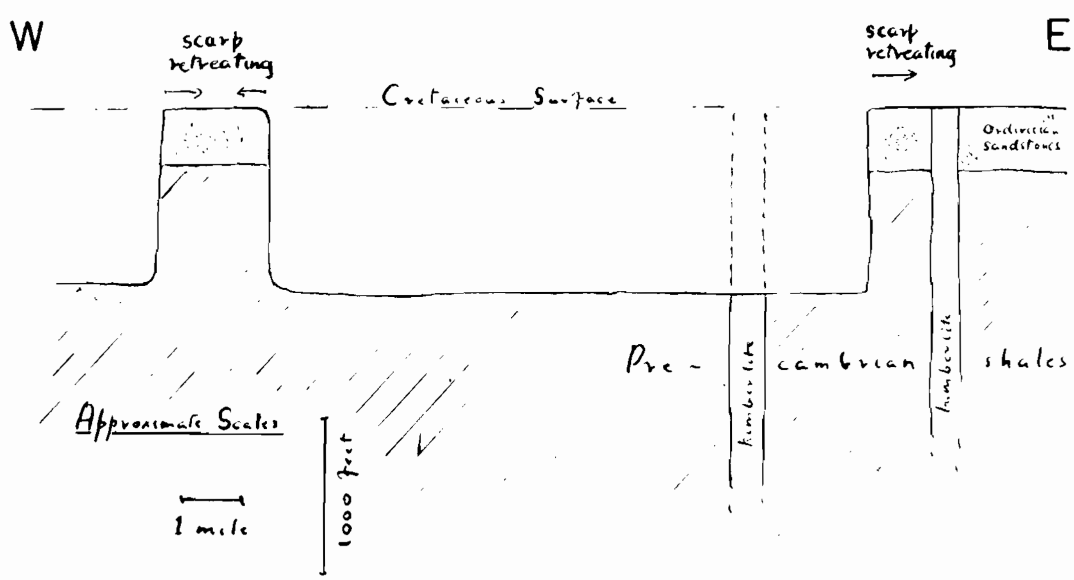


FIGURE 4

distributed over the area of the present plain by rivers flowing on a high erosion surface that has now disappeared. This means that any stream may contain heavy minerals which it has never had the competence to move. The other peculiarity of the streams is that they have aggraded and are flowing, with a very low gradient, at a level above the lowest level of degradation. One of the consequences is that most of the coarsest particles lie too deep for sampling. Another is that the streams are of very low competence.

Except near the escarpment where the streams are swampy, the sampled material was a mixture of quartz sand, lateritic pisolites, and fragments of vein quartz. Pieces of lateritized rock are common; in some places there are also pebbles of a hard quartzite. Clay is ubiquitous. Only in rare places has the Precambrian shale survived pre-erosional decomposition. The lateritic pisolites which form an important proportion of many samples have a density of between 3.0 and 3.5.

Samples were usually taken in places where the range in grain size was large. Most samples contained both gravel and clay.

Initially the sample size, five litres, was measured in the field. Latterly this measurement was only approximate as the volume of each size fraction was measured separately during treatment. For panning each sample was separated into sizes: 10, 6, 4, 2, 1, ½, ¼ and -¼ mm. The concentrate was then recombined and a heavy mineral size analysis made after drying.

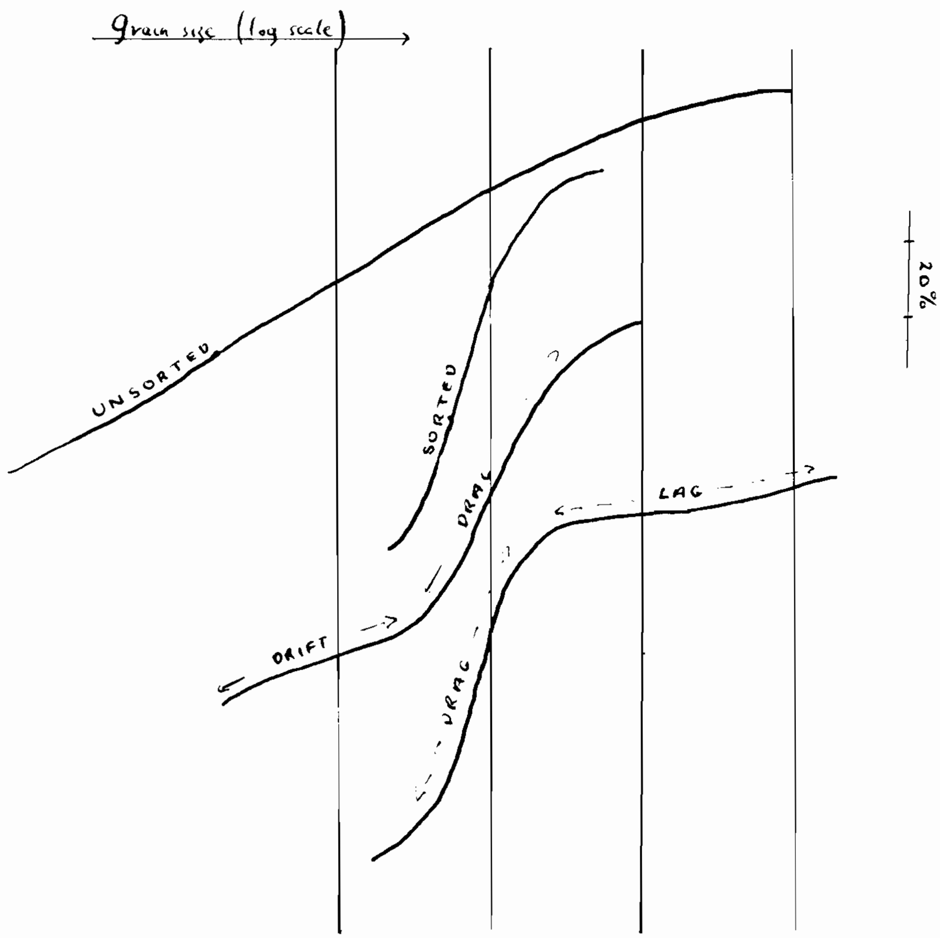
THE USE OF CUMULATIVE CURVES

Cumulative curves are used instead of histograms for plotting size distributions because the shape of these curves does not depend on the size fractions used. A logarithmic scale has been used for the grain size and an arithmetic scale for the percentage. The "steepest" part of the curve corresponds to the maximum of a frequency curve. It follows that the steeper the curve the narrower the corresponding frequency curve and, for sediments, the better the sorting. Similarly, a cumulative curve with a gradual slope from coarse to fine corresponds to a broad frequency curve, or to a poorly sorted sediment.

Examination of a large number of cumulative curves for heavy minerals in sediments shows that in nearly every case the curve can be considered in three separate, characteristic parts. Of the three terms used to describe these parts, two, "drag" and "drift" have been coined for the purpose. The other term, "lag", is well known.

The steep part of the cumulative curve spans the sizes of heavy minerals which are most abundant and best sorted. These have been called the drag sizes, because, as explained later, they appear to have a very slow rate of movement relative to the rest of the sediment. The flat part of the curve (Figure 5) to the right of the drag sizes is called "lag", as it appears to be formed by grains too heavy for transport. On the left hand side, the "drift" part of the curve, which is not always present, appears to be formed by minerals of smaller sizes which are readily transported.

CUMULATIVE CURVES SHOWING NATURE OF "LAG", "DRAG" & "DRIFT" SIZES



For explanation see text

FIGURE 5

STATEMENT OF THEORY

For the sake of clarity the theory is here stated alone. The next section contains the facts to support and the arguments to justify it.

It is fundamental to the whole theory that the heavy minerals found in sampling the sediments in a stream are those which are sorted and moved only when the stream is at its maximum transporting capacity. Those that are moved when the stream is flowing more gently are removed at flood time and are not therefore available for recovery during sampling.

The competence of a stream is limited. There are therefore sizes of heavy mineral known as the "lag" sizes which are effectively unmoved and unsorted.

There are other sizes, so small that they are swept away as fast as they are produced by erosion. These, the "drift" sizes, are not usually recovered.

Between these two, the lag and the drift, there is a size group, called the "drag" sizes, which are moved but only slowly. These drag sizes are only slightly smaller than the lag sizes which are unmoved. Accordingly, they are not readily transported, and they become concentrated by scouring in the same way as lag sizes. Evidently each scouring action lowers the accumulated products of all lesser scours. There is, therefore, an increasing abundance of heavy minerals with depth. The concentration of lag sizes by scouring is discussed more fully in Addendum 5.

The steep part of a cumulative curve corresponds to the drag size and if there is more than one steep part the drag size is the smaller. (Figure 5) The presence of larger grain sizes could be due to derivations from a higher surface (Addendum 6) or to alluvial concentration under other conditions. Either way they are lag sizes now. Lag sizes are shown in Figure 5. Note the lack of sorting.

The problem is best considered in terms of dynamic equilibrium. The lag sizes are never perfectly in equilibrium as there is always the statistical possibility of peculiarly powerful turbulence which would be capable of moving them. There is, therefore, a tendency toward removal but since the rate of removal is so small it is effectively nil. There is metastability. The drag sizes achieve their stability by a dynamic balance between rate of removal and rate of replacement. For smaller sizes the rate of removal exceeds the rate of replacement; in a sample, therefore, they are absent. Near a source, however, the rate of replacement of the very small sizes is so great that however fast they are removed they are replaced. Stability is achieved through a dynamic balance. The situation is comparable to that of sand in a mountain stream; it is always there, not because it never goes, but because it is always replaced.

In parts of the stream unaffected by a local source the mean size depends first, on the competence of the stream and second, on the actual (geologic) availability. The availability at any single point is only what the stream has transported to that point. The mean size is therefore reasonably constant along any short length of stream or for as far as the competence remains unchanged.

A source shows itself in two ways, each of which involves an upsetting of the balance between rate of removal and rate of supply. Near a heavy mineral source, the indication lies in the presence of drift sizes. Only near a source is their super-abundance sufficient to balance removal. Farther downstream from a source, indications of its whereabouts can only be found at confluences. Here a stream contributing a suite of heavy minerals different from those of the main stream must affect the mean grain size of heavy minerals from samples taken just downstream from the confluence. Comparison of the cumulative curves for samples taken above with those taken below the confluence shows the effect of the tributary. This difference could be due to a different stream gradient or to a different type of heavy mineral supply.

The drag sizes are only slightly smaller than the lag and they are certainly more resistant to transport than the bulk of the sediment. If this were not so they would not be concentrated. If scouring is effective in lowering the drag sizes, as theory expects of the lag sizes, there will be a greater abundance of heavy mineral at greater depth.

The only variable, then, controlling the amount of heavy minerals in a sediment is a quantity that can never be measured. Assuming a constant rate of heavy mineral supply this quantity is the time that has elapsed between the last scouring below a certain level and the next scouring to the same level. The longer this time interval the greater will be the amount of heavy minerals accumulating in higher levels. At the end of the time interval this accumulation of heavy minerals is lowered to the level in question.

JUSTIFICATION OF THEORY

Data from Kenieba

The following pages are to justify and elaborate the theory set out in the previous section. There are two main aspects to this theory: the relative amounts of heavy minerals of different sizes and the comparison of the quantities of heavy and light minerals in the same sample. The evidence supporting the theory of size distribution is, it seems, convincing but as there was no attempt to take a series of samples at different depths in a stream bed, the justification for the aspect of the theory explaining quantities is more indirect.

For any particular stream the break between the lag and the drag section of the cumulative curves occurs at much the same size. This is evident in Plate 3 in which the break for most samples is at about 0.2 mm.

Not only is the quantity of the material shown in the lag sizes very variable but it may be present in one sample and absent in an adjacent one. When this happens the drag sizes are unaffected. Compare, for example, samples 249 and 250 (Plate 3); these were taken within five metres of each other.

Plate 4 with plans and cumulative curves for two places on the lower Doundi River, shows the relationship between lag and transported sizes in a number of samples. Note how the shape and positions of the curves for the drag sizes (-0.2 mm) are generally the same. So are the median sizes, and to some extent, the quantities.

The lag sizes show no sign of sorting. There may be equal quantities of several size grades or there may be either an increase or a decrease in quantity with increasing size.

Lag sizes are most abundant in streams near the foot of the scarp where one would expect some of the material in the stream to be derived from a higher, vanished erosion surface. See samples 1 - 17 and 173 - 179, Plate 5.

There seems little doubt that the lag sizes are too large for the stream to transport. They are unsorted, occur where their presence can be explained without invoking longitudinal transport and are immediately larger and are clearly different from the drag sizes which show every sign of sorting. Samples within a few metres of each other: 237, 234, 233, 235 (Plate 4) show absence, trace, or relative abundance of the lag sizes. Sample 235, for example, shows only a negligible quantity of ¼ mm. minerals, although further upstream in sample 237 this size forms an appreciable quantity of the whole. Similarly, sample 241 shows hardly any of the lag sizes although nearby sample 240 has a smaller volume of concentrate yet an appreciable quantity of the ¼ mm. fraction.

Plate 3 indicates a similar situation. The difference between samples 251 and 252 is obvious. The lag sizes in sample 252 could have come from the gold washing of gravel nearby or they might be derived residually from a higher erosion surface.

(Addendum 6) If the cumulative curve for sample 252 were replotted omitting the lag sizes it would be found to correspond well with that for sample 251.

The drag size fraction of the cumulative curve is the most important part of nearly every one; in many, the other parts of the curves are negligible. For any one stretch of stream the mean drag size is remarkably constant whether or not drift and lag sizes are present. That it is sorted seems indisputable in the light of comparisons between the drag size section of a cumulative curve and the distribution in the source rock. (Figure 3) Some samples have lag sizes while in othere nearby these sizes are absent. This indicates that there is at least enough sorting to separate the drag sizes from the larger sizes.

Sample 249 (Plate 3) plotted as an ordinary frequency curve shows bimodally. If the larger modal size was what the stream moves now, the presence of smaller sizes could only be explained by a greater availability or by a different sedimentation process. The persistance of the mean size close to 0.2 mm. is not, therefore, the only reason for believing these sizes to be concentrated by slow transport. For if they were due merely to superabundance of minerals of this size despite the fact that there was a tendency for them to be swept away, then some evidence of sorting would be expected in the larger sizes. None of the samples illustrated in Plates 3 and 4 show any evidence for this sorting of the larger sizes. There is a possible exception in sample 252 but when the size distribution of this sample is compared with those for samples 3, 4, 5 and 7, all of which came from a stream certainly capable of transporting larger minerals, it becomes evident that the larger grains of sample 252 are not sorted.

The Middle Doundi River (Plate 2) shows the same difference between the sorted, -0.2 mm. and the unsorted + 0.2 mm. sizes. The two exceptions, samples 256 and 257 are possibly located near sources of kimberlite where the abundance of all sizes overwhelms the sorting of the stream.

Size distribution of samples from the Dijiamba downstream of Segala (Plate 1) is confusing as the greater part of the gravel in the channel was carried there by gold diggers and the same almost certainly applies to the concentrate. However, a slight steepening of the curve at about 0.12 mm. may indicate the real transporting power of the stream.

Samples 131 to 135 were taken in a pile of gold tailings. They show a slight increase of mean size with depth. More important, only those samples containing a layer of coarse material on fine (131 and 135) have a significant proportion of lag sizes. This is interpreted as being evidence that lag size grains are rare, because of their transience, in levels of frequent scour. Only in levels that collect the products of many scourings are they at all abundant. Evidently, since the gravel was deposited on the sand no scouring has been deeper than the present contact between them. Frequency of scour probably decreases from the

.surface to the gravel-sand contact at which it is zero. (Figure 6)

DIAGRAM SHOWING THEORETICAL RATE OF LOWERING OF HEAVY PARTICLES IN A STREAM BED

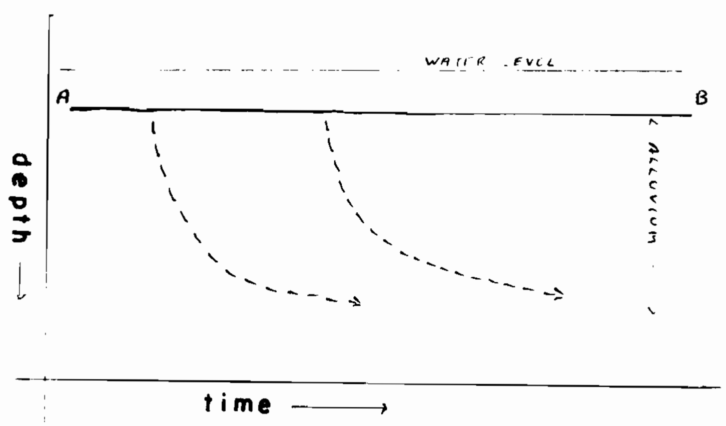


FIGURE 6

The lag sizes drop out beyond the gold digging area. Samples 156, 157, 143, 144 and 145 have no heavy minerals over 1 mm. and only traces of any size above 0.15 mm.

Sample 196 was taken from the coarsest gravel in a pit on the inside of a sharp bend in order to obtain transported material that had not been contaminated residually or artificially. It seemed a suitable place as therewas no residual gravel for about a hundred yards upstream. All the heavy minerals found in this sample were smaller than 0.42 mm. but it was not possible to be sure that the material sampled was the most likely to contain coarse grains.

Samples 164 and 165 were taken from a coarse grained sub-angular to subrounded quartz gravel where the stream runs through an area that has been intensively mined for gold. There is no sign of separate lag and drag sizes; these unsorted, large heavy minerals can be attributed to local introduction. All the samples upstream of this place were obtained from gold tailing gravels.

The first six curves shown in column 1 of Plate 5 are from samples in the rocky stream between a waterfall over the scarp and the sandy channel which begins three hundred yards downstream. From the appearance, the gradient, the coarse gravel and boulder beds there can be little doubt about the channel's ability to move the larger sizes of heavy mineral. Sample 5, for instance, is from a grit beneath a very coarse boulder bed. The curves, too, indicate a competent stream as the drag sizes are much larger than are found elsewhere.

Curves similar to those of samples 3, 4 and 5 might be produced by the concentration of minerals during lowering from a higher erosion surface. This process involves a progressive winnowing away of the lighter material leaving the heavier grains preferentially concentrated. As there are plentiful small sizes in sample 7, for example, this size distribution is more likely to have been produced by fluvial than by deflationary concentration.

Further downstream, despite the fact that the channel is sandy (or coarser) the general tendency for a modal size around 0.12 mm. seems to indicate the transporting ability of the stream.

The variety of sample sizes can be explained to a great extent by Figure 6. This diagram shows the consequences of decreasing frequency of scour with depth. Evidently there will be an increase in the quantity of heavy particles with depth (assuming their constant rate of arrival) because heavy particles that were on separate scour levels when they were in shallower alluvium become telescoped into the same scour level when they are lowered.

If the topographic surface of the bed of the stream were not so simple as line A-B but undulated above and below it, a variation in the quantity of heavy minerals in a given volume of sediment would be expected.

Samples 500 to 522 which are conspicuously devoid of lag sizes were chosen to test the degree of correlation between

1. The light mineral mean size and heavy mineral mean size.
2. The light mineral mean size and the heavy mineral quantity.
3. The quantity of heavy and the quantity of light minerals of equivalent hydraulic size.

It can be seen from Figure 7, 8 and 9 that there is no simple correlation. On the other hand, the comparative constancy of the mean grain size or its systematic variation show that the heavy mineral size distributions are not randomly controlled. The position of these samples is shown in Figure 11.

Samples 301 to 310 (Figure 12) were all taken within a hundred yards of each other in a rock bar. The samples were approximately the same volume. No attempt was made to select any particular grain size of sediment. All but one (304) of the samples was taken in a lateritic grit with quartz fragments and clay. Some were collected from pot holes and the rest from shoals of grit resting on hard rock. The heavy mineral size distributions are remarkably constant.

FIGURE 7

showing lack of correlation between the mean grain sizes of light and heavy minerals in the same sample

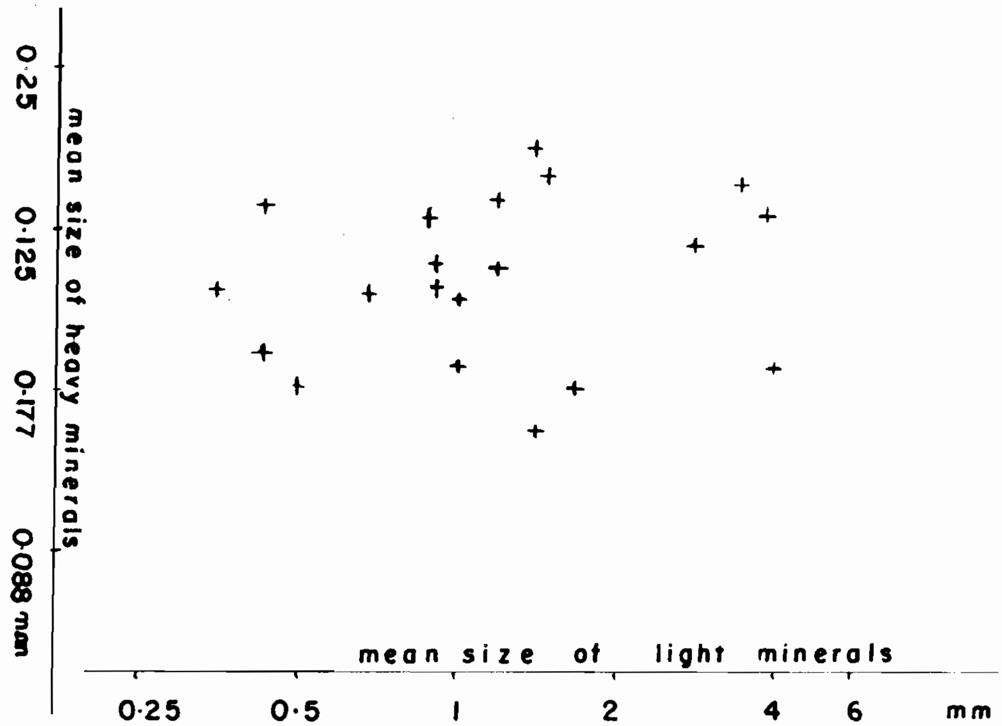


FIGURE 8

showing lack of correlation between the mean grain size of the light minerals and the total quantity of heavy minerals in the same sample

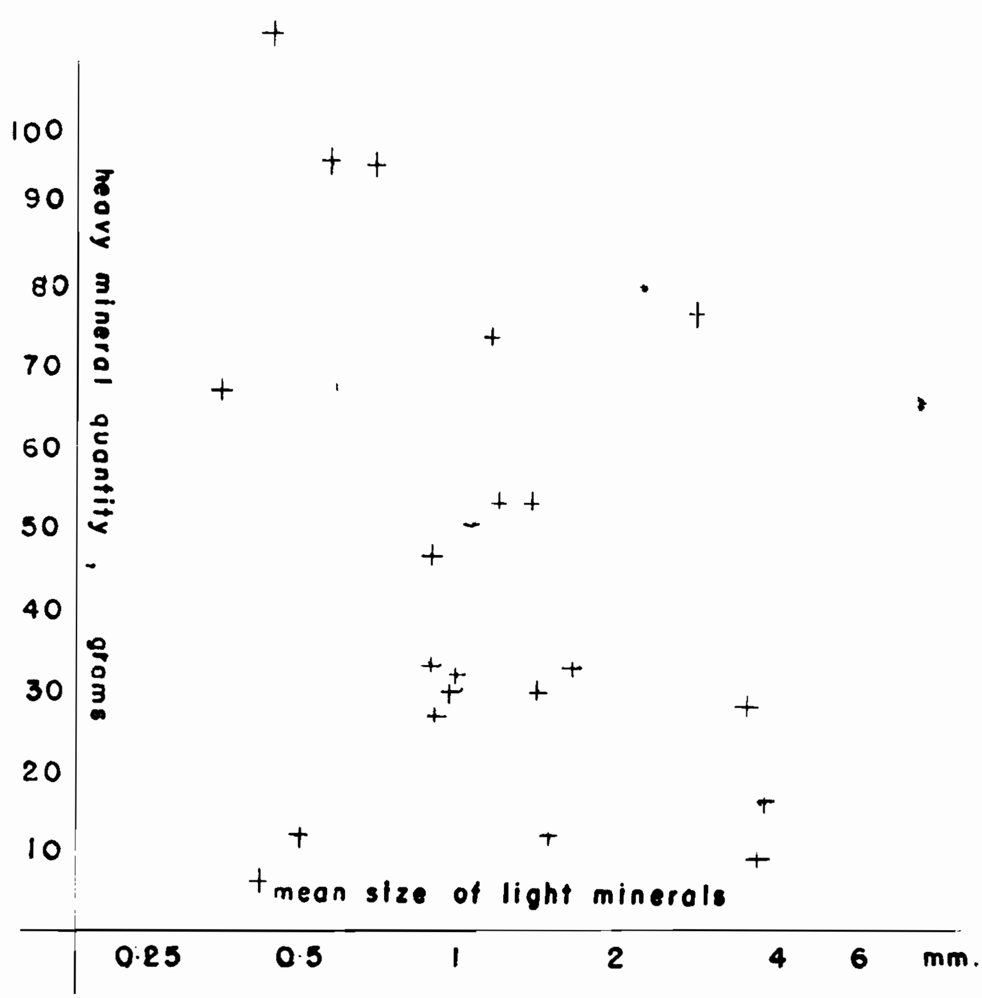
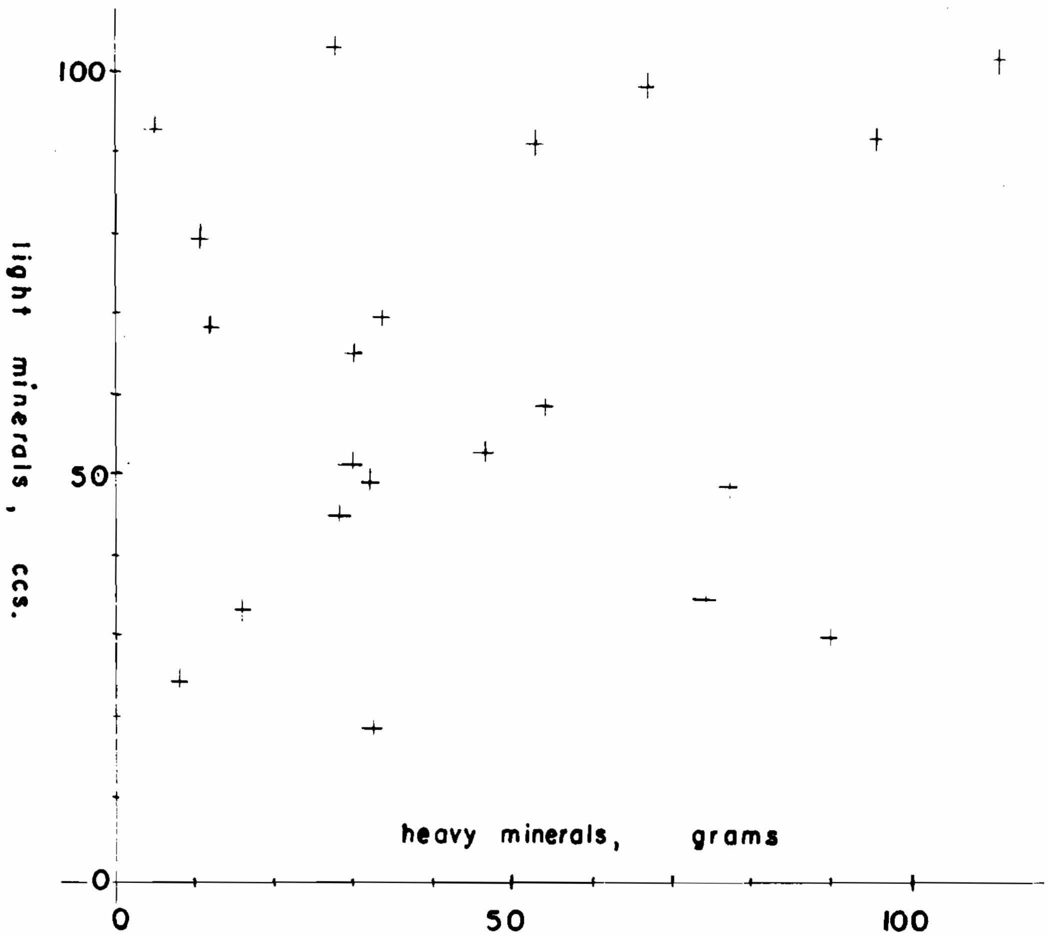
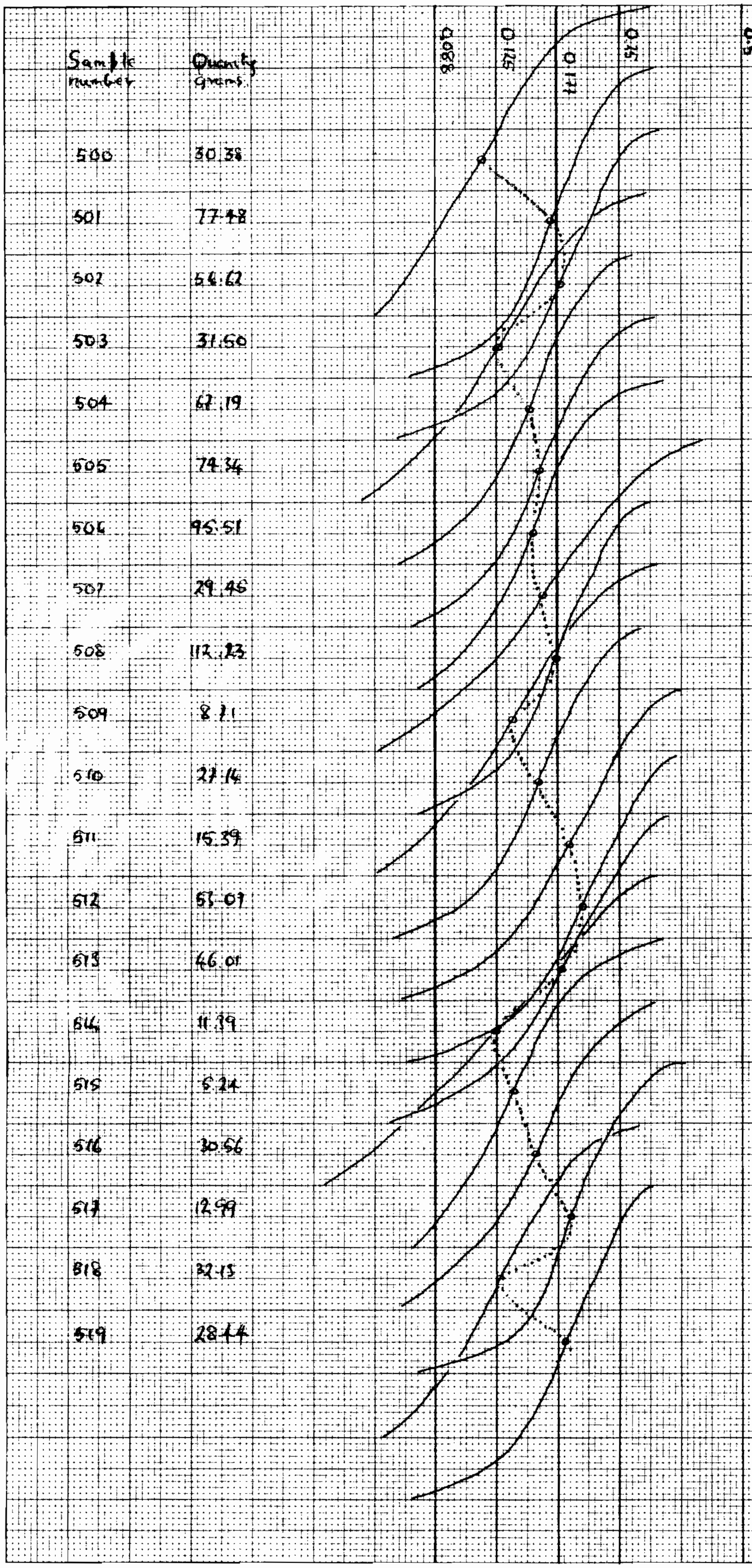


FIGURE 9

showing lack of correlation between the quantity of heavy minerals and the quantity of light minerals of one phi size larger



for explanation see text



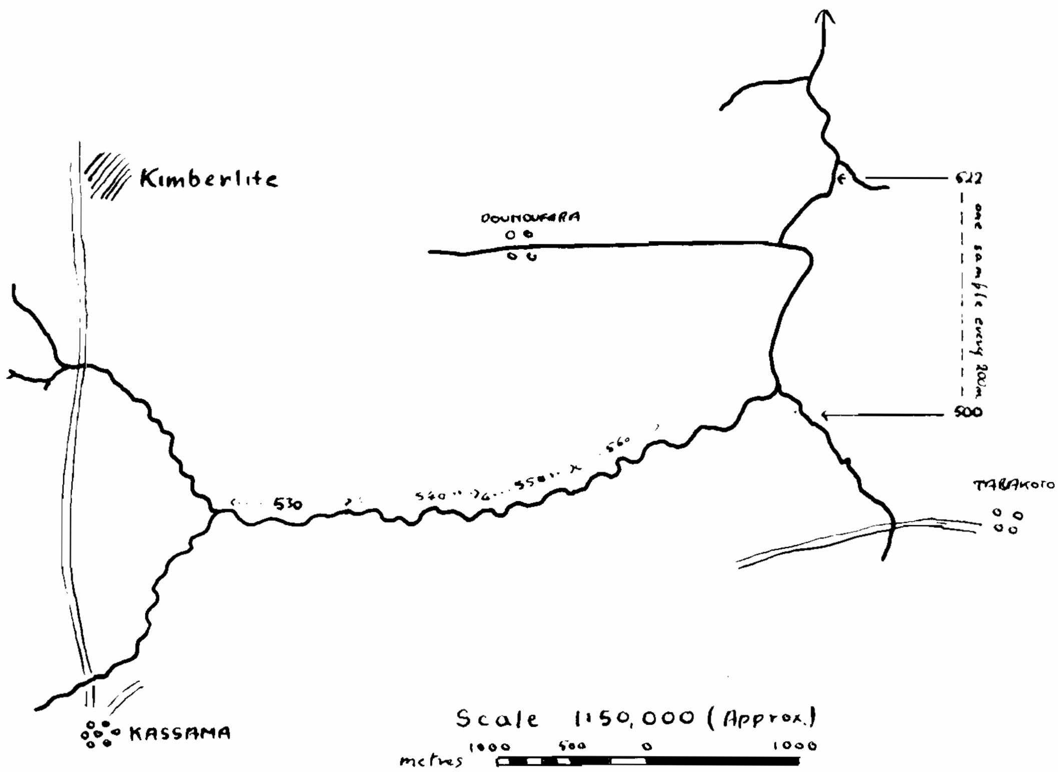
HEAVY MINERAL SIZE DISTRIBUTIONS for SAMPLES 500-522

Mean sizes are joined by the dotted line

FIGURE 10

FIGURE II

Plan showing position of kimberlite and of samples 500-522 & 530,40,50,60



Plan traced from aerial photographs.

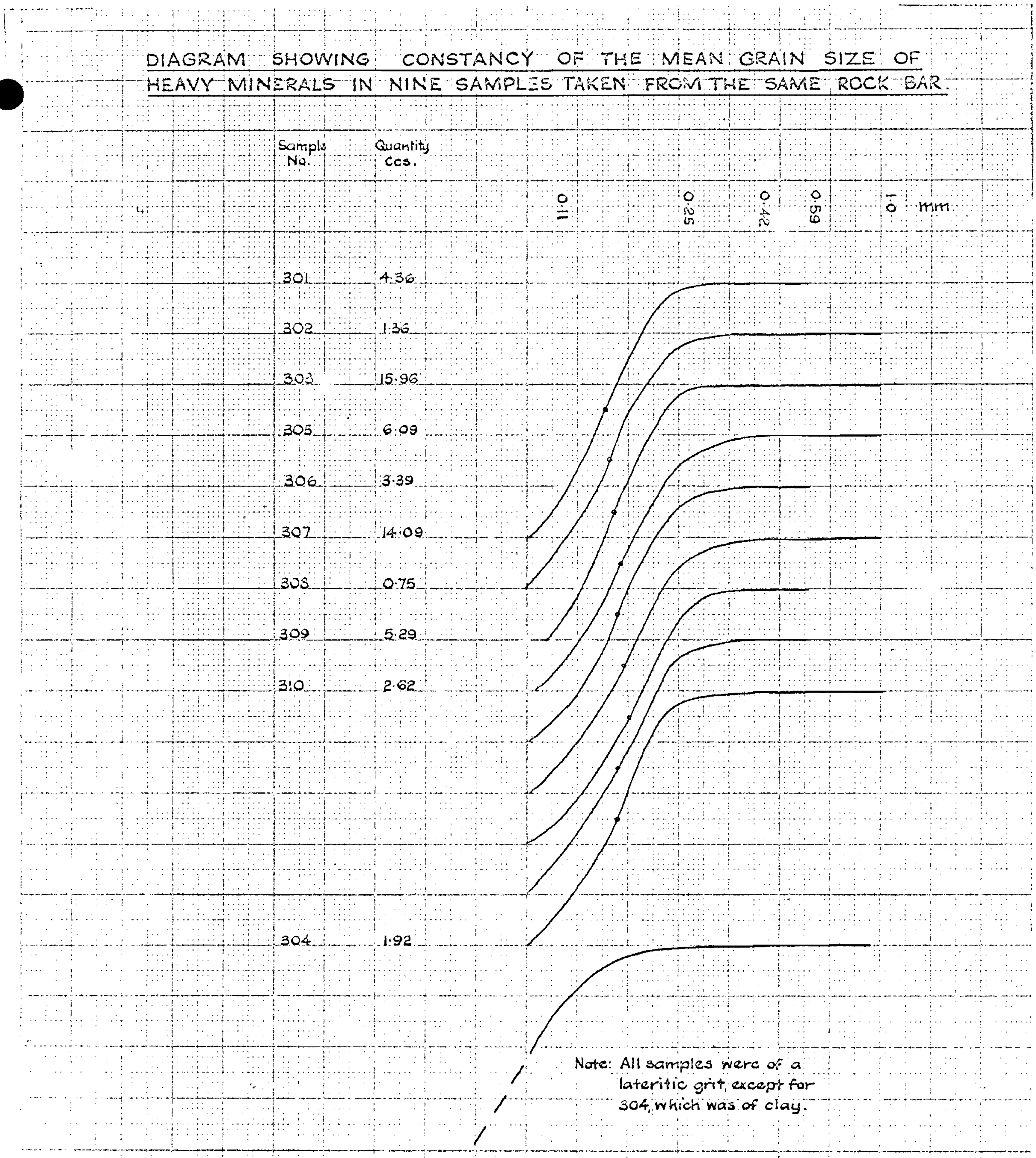


DIAGRAM SHOWING CONSTANCY OF THE MEAN GRAIN SIZE OF HEAVY MINERALS IN NINE SAMPLES TAKEN FROM THE SAME ROCK BAR.
Sample No.
Quantity Ccs.
0·11
0·25
0·42
0·59
1·0 mm
301 4·36
302 1·36
303 15·96
305 6·09
306 3·39
307 14·09
308 0·75
309 5·29
310 2·62
304 1·92
Note: All samples were of a lateritic grit, except for 304, which was of clay.

FIGURE 12

Laboratory Analysis

Samples 500 to 522 on which a size analysis had already been made in the field were analyzed again in the laboratory. An account of the procedure used is contained in Addenda 1 and 2.

The means of the grain size analyses produced by field and laboratory methods are compared in Figure 13. Although a comparison of means is not the most sensitive test for discrepancies it is a useful comparison to make as the mean size was used for comparing the change in size distribution along the length of a stream. The field analysis appears to have been adequate as all major mean size fluctuations shown in the laboratory analyses are also indicated by the field analysis. The slight difference can be partly ascribed to the change from volumetric to weight analysis and partly to the greater number of measurements (four instead of two) in the critical size range.

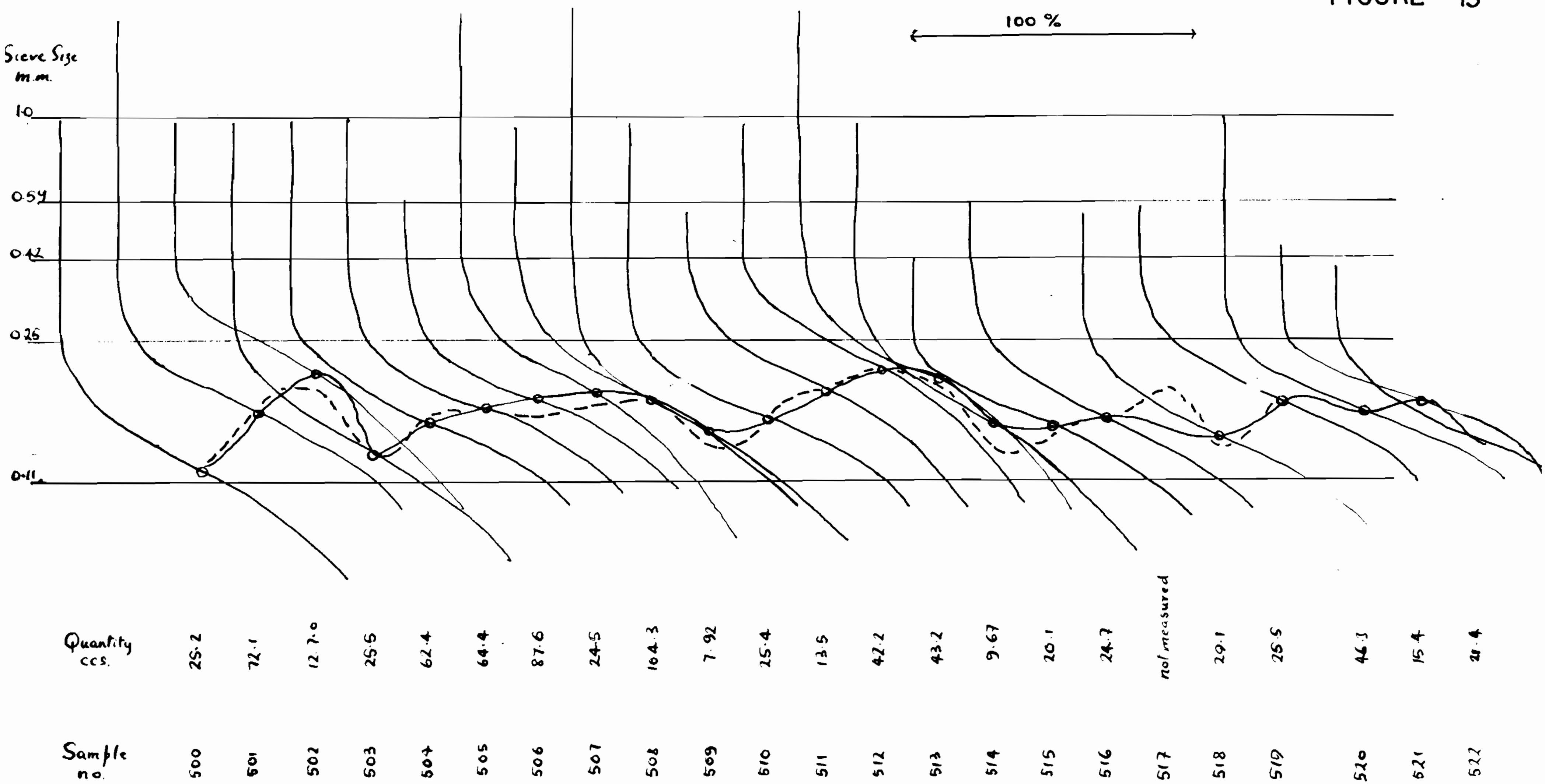
Time was limited and investigations to find the nature and perhaps the cause of the fluctuation in grain sizes along the length of the stream were confined to five samples which spanned the confluence with a stream draining a kimberlite pipe.

The two smallest size fractions were chosen for analysis as it was in these fractions that the tributary appeared to have most effect in altering the size distributions in the main stream. In sample 502 the -0.088 mm. fraction is almost absent; in sample 503 this size forms about 20% of the sample.

A COMPARISON OF FIELD AND LABORATORY SIZE ANALYSES

Cumulative curves show the results of volume analysis in the field. The proportion of heavy minerals in the final concentrate was estimated visually. The mean sizes are joined by the continuous line. The broken line joins the means of a similar series of cumulative curves plotted from the results of laboratory analysis

FIGURE 13



One attempt to detect a difference in the mineralogy of the samples before and after the confluence involved measurement of the magnetic susceptibility. (Addendum 3) No difference was evident.

X-ray fluorescence analysis of the same fractions showed that the first sample after the tributary (503) had a lower proportion of zirconium and a higher proportion of chromium, titanium, nickel and vanadium than samples further upstream. This is largely because the main stream contains more zircons than the tributary. It was not possible to establish any other significant difference. In the tributary, however, there was a steady decline in the Cr/Ti ratio from the source of the stream where the ratio was nearly as high as in pure kimberlitic ilmenite. In the main stream at the confluence this ratio is higher than what would be expected for a stream draining only dolerite. Possible both tributary and main stream are draining areas in which kimberlites are present.

This work suggests it may become possible to use the size analysis of heavy minerals in prospecting for certain types of ore body.

LIGHT MINERAL SIZE DISTRIBUTION for SAMPLES 512 - 522

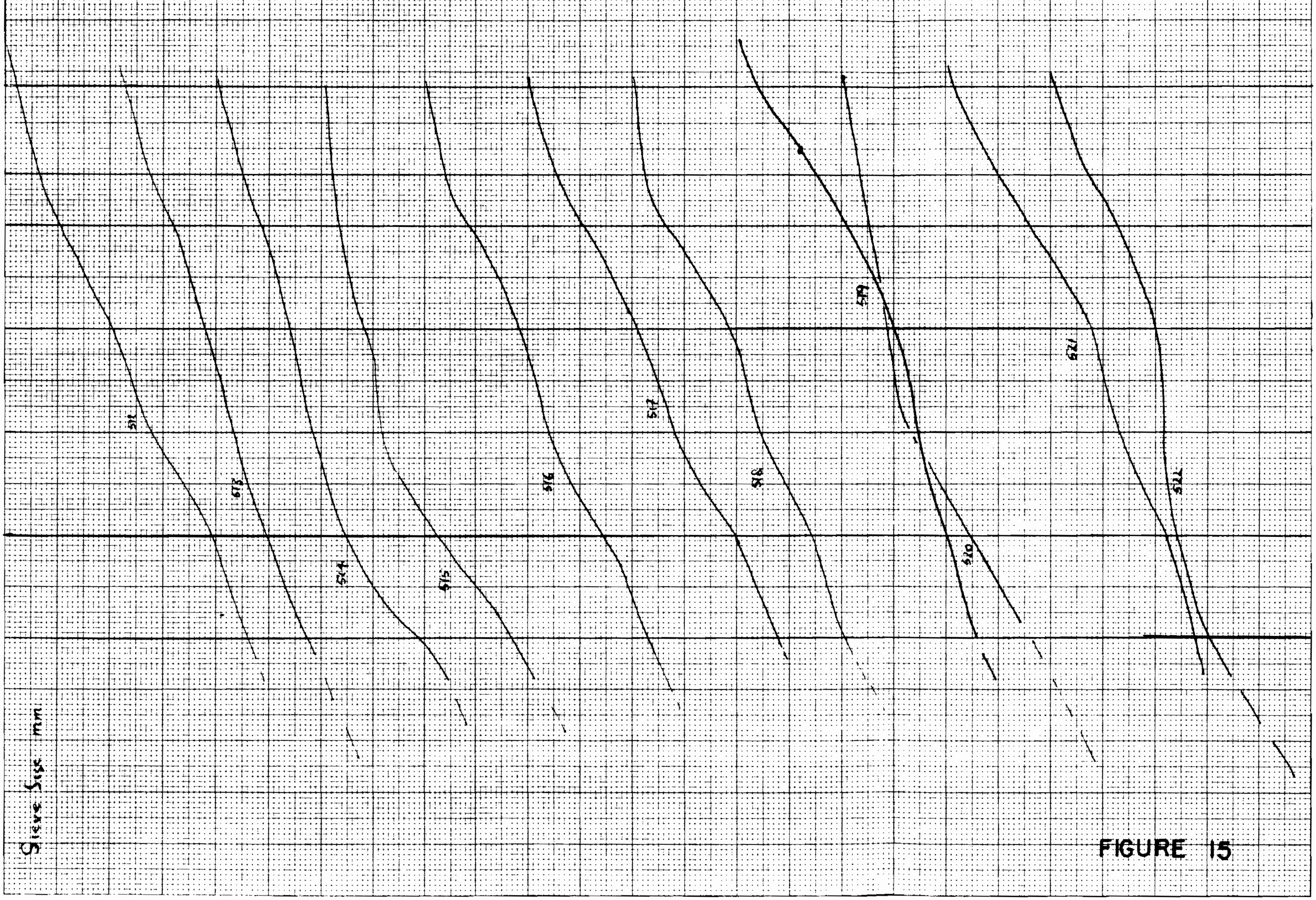


FIGURE 15

LIGHT MINERAL SIZE DISTRIBUTION for SAMPLES 500 - 511

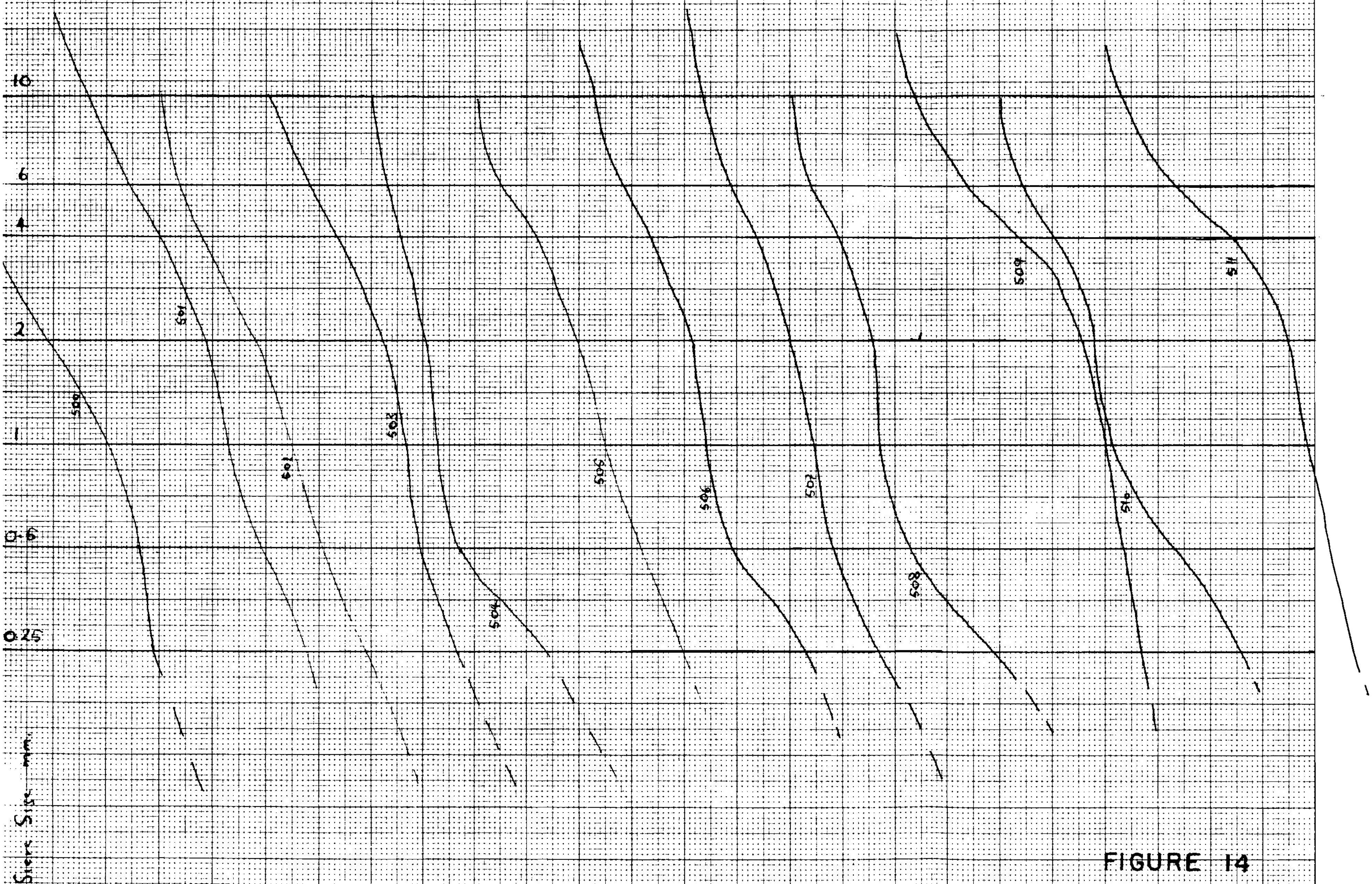


FIGURE 14

Other Data

Moss (1962) demonstrated the differing roles of the saltating, rolling and sliding grain movements in the formation of sandy and coarser deposits. Given, as we have seen, that the drag sizes are almost as large as the lag sizes, it seems improbable that they are moved very readily. For a light mineral of marginal moveability this would be by rolling or sliding. But, because of the relatively uneven surface that larger grains would provide, it is impossible for the heavy minerals to slide or roll over a stream bed composed of grains larger than themselves. So a heavy mineral grain remains stationary until it can be moved by saltation. This gap in the normal series of transport mechanisms may go a long way towards explaining the sharp demarcation between the lag and drag sizes of a heavy mineral sample. It is evidently much more pronounced than for light minerals (compare Figure 10 with 14 and 15, the one for heavy minerals, the others for light).

Although it appears from this argument that most drag sizes are moved by saltation, there is no evidence that the net rate of transport is other than very slow. After returning to the bed of the stream a heavy mineral grain will usually occupy a position interstitial to the larger, light minerals. Thereafter the probability of its immediate movement is small. The net rate of transport is slow even though while it is in motion it is moved quickly.

DISCUSSION OF HYDRAULIC EQUIVALENCE

The theory of heavy mineral transport developed to explain the data from the Keniaba samples conflicts with much of what has been written on the transport and deposition of heavy minerals. In the following section the data and deductions of Rittenhouse's paper (1943) are discussed in the light of those from Kenieba. One cause of the factual disparity may be that each investigation was carried out in a different type of alluvial regime. Nevertheless, in each case, the theoretical explanations have been extrapolated to be of more general significance and application.

Rittenhouse's main contention: "There seems to be little doubt that the size distributions of heavy minerals vary systematically with the differences in average size and degree of sorting of the deposits in which they were found." appears to contradict directly the Kenieba findings. The evidence, however, is not so conflicting.

Examination of the size distributions from the Rio Grande which was studied by Rittenhouse, showed that the heavy minerals were predominantly in the drag sizes. (Figure 18) There were some samples with lag sizes but in most they were negligible. The samples were from two inch diameter cores forty inches long sunk into the bed of the stream. The two main disadvantages of this kind of sample are: first, it averages out variations in a multitude of sedimentation units, and second, it is not at all improbable that the transporting capacity of the river changed in the course of the time represented by the forty inch cores. If this was the case the coarser nature of some of the samples relative to the others could be due to their having tapped a layer representing greater stream competence. A greater stream competence involves an increase in the size separating drag and lag sizes. In other words, assuming they were available at source the mean size of heavy minerals which were locally available would be greater in any layers that were deposited when the stream was more competent.

This is in no way the same as attributing the size variation to local sorting or to hydraulic equivalence. According to the hydraulic equivalence hypothesis two sediments, one fine and one coarse, would have, respectively, finer and coarser heavy minerals. According to the theory developed for the Kenieba data the heavy mineral size distribution of both the coarse and the fine sediment would be the same. When, however, the stream conditions changed and thereby altered the local availability of both heavy and light minerals, there would be a change in heavy mineral mean size in sympathy with the light mineral changes. This would only be true, of course, provided the heavies were available for transport from further upstream.

Figures 16 and 17 are two cross sections of a river to explain how this may happen. In Figure 16 the lower and upper levels show respectively coarser and finer deposits of both light and heavy minerals. The lower bed was laid by a stream during greater transporting capacity than when the upper bed was deposited. The heavy mineral availability is the same throughout any single bed. If we assume, following Kenieba data, that the heavy mineral size distribution is not dependant upon the sediment grain size, then

CROSS SECTIONS THROUGH A STREAM BED

for explanation see text

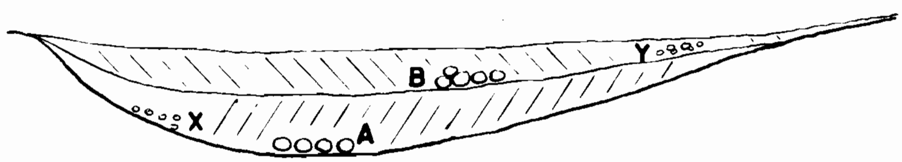


FIGURE 16

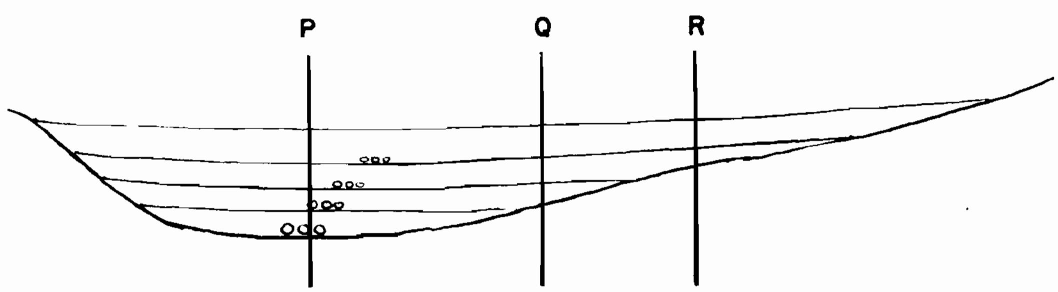


FIGURE 17

samples at A will yield the same heavy mineral distribution as at X. Likewise, at B there will be the same size distribution as at Y. Both A and X will have coarser mineral suites than B and Y.

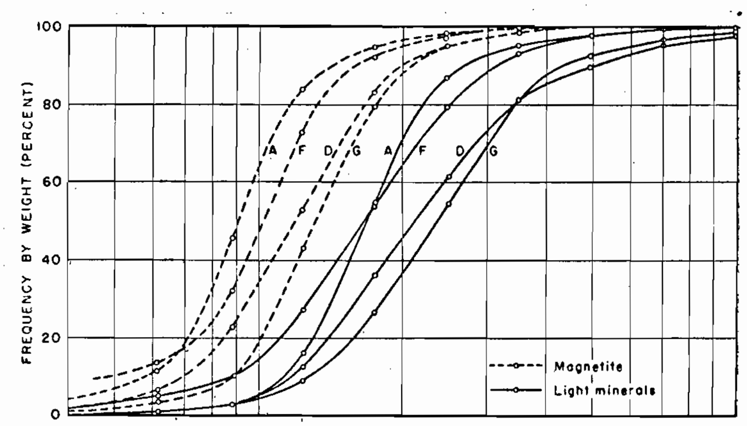
Figure 17 is similar to Figure 16 but it shows four beds representing, with increasing depth, an increasingly competent stream. Samples R to P tap beds of increasing coarseness. Sample P therefore contains the coarsest material and as this was deposited during a competent phase of the stream the heavy minerals in it are coarser because the stream was at the time capable of moving coarser minerals. There is therefore an apparent correlation between sediment grain size and the grain size of the heavy minerals contained in them.

In the light of these arguments, the data from the Rio Grande supports the theory of hydraulic equivalence no better than it supports an opposing theory. Only further work with samples spanning a much smaller depth range will resolve the problem.

Figure 18 from Rittenhouse's paper (part of his Figure 3) shows a proportion of what appear to be lag sizes in samples D and G. It is not altogether meaningful to consider lag sizes in a sample containing sediment deposited under a wide range of conditions, as what is "lag" for one condition may be transportable under other conditions.

Even so, it is worth remembering that if the heavy minerals and sediment are from the same source, sympathetically varying proportions of lag size sediment alone will produce an apparent correlation between the light and heavy minerals. With every increase in stream competence there is an increase in the maximum grain size transported. This is true for both light and heavy minerals. Provided, therefore, both are available, an increase in stream competence increases the transported sizes of both light and heavy minerals. In this way the sizes of light and heavy minerals in the same sample change sympathetically. The resulting

FIGURE 18



Cumulative curves for light & heavy minerals
(from Rittenhouse, 1943)

correlation, therefore, is due not to local hydraulic conditions but to the local availability of each being controlled by changes in stream competence.

The essence of the hydraulic equivalence hypothesis was expressed by Rittenhouse (p.1742) as follows: (Numbers refer to comments below.)

> "In addition, at different times or at different places in the stream, the absolute availability of any size of grains will vary because of differing hydraulic conditions.(1) Thus, during high flows more and coarser

sand will be transported than during low flows. Under varying hydraulic conditions, however, the relative availability of grains of any given equivalent hydraulic size should remain the same. If more light minerals are transported as the stream discharge increases, more heavies of hydraulic equivalent size will be transported. (2) If this were not true, then the heavies and lights would not be of the same equivalent hydraulic size. (3)

"Similarly, when heavy minerals are deposited, light minerals of equivalent hydraulic size will be deposited in the proportion in which they are available in the stream load. (4) Consequently, the relative availability should be a constant that is common to the stream load and to all deposits from that stream load, regardless of the differences in absolute amounts of the minerals of the same and other sizes that are deposited under the particular hydraulic conditions existing at different places of deposit."

1. The data from Kenieba suggests that local hydraulic conditions do not alter the availability of any grain size of heavy mineral.

2. This depends on an over-simplification of transportational processes. Two minerals may be "equivalent" under Stokes-Law conditions, but this is no reason why they should have a similar equivalence under other conditions. Sediment is moved as bed load and suspended load or as rolled, sliding and saltating load (Moss 1961). The mechanics of transport are utterly different. Consider, for instance, the effect of a coarse stream bed on rolled heavy minerals of a size which is interstitial to the coarser particles.

3. The logic of this sentence depends entirely on the validity of the concept of "hydraulic equivalence".

4. But these proportions change as soon as the conditions at the

site of deposition are no longer those of the settling tube.

Rittenhouse points out the apparent correlation between light and heavy mineral sorting in samples A and F (Figure 19) He cites this "same general shape" of the cumulative curves as evidence of sympathetic reaction to local hydraulic conditions.

FIGURE 19

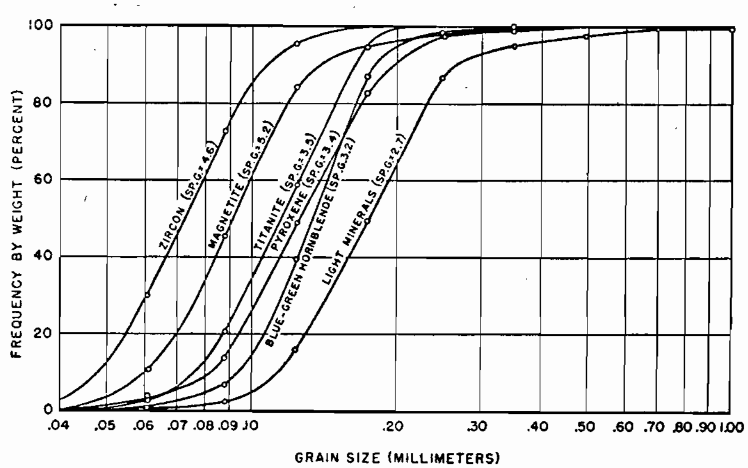


FIGURE 2.—*Size distribution by weight of light and selected heavy minerals*

Sample A

(from Rittenhouse, 1943)

In fact, all this means is that the type of size distributions are similar, probably Gaussian, for all types of mineral.

Invalidation of the concept of hydraulic equivalence does not mean that all the deductions based on it are themselves invalid. Rittenhouse found that the hydraulic ratio was diagnostic of sediment sources. The hydraulic ratio is the quantity of heavy minerals divided by the quantity of light minerals of equivalent hydraulic size. This quantity measured over a sufficiently large number of sedimentation units is merely a measure of the bulk ratio of heavy mineral to a particular grain size of light. That it is constant along the length of a stream or that it is diagnostic of certain tributary streams is not surprising, as stream sediments tend to reflect the characteristics of rocks from which they were derived.

Rittenhouse concluded that in addition to the variations explicable in terms of hydraulic conditions and of availability there are other variations that can only be explained by "some factor or factors now unknown". It is most improbable that so complicated a set of conditions could be completely explained mathematically. But the fact that the hydraulic equivalence theory has been found wanting in some respects may be significant in the light of the argument that it is invalid. As previously mentioned, the reason it appears to explain so much may only be that there were relatively large numbers of "sedimation units" in each sample.

FUTURE WORK

Future work will involve investigations in at least three different directions. First it will be necessary to test the validity of the theory propounded in this paper in several different types of stream. Second, the theory of the progressive concentration of both heavy minerals and lag sizes with scouring of the river bed must be tested. The results of samples from actual and ancient river channels should be compared with those from flume studies in which the scouring can be controlled and recorded. Third, and potentially the most important, will be further work into the persistence with distance of mineral characteristics. At present little is known about the effects of concentration, dilution, fragmentation and differential rates of transport on heavy minerals. It has been shown in this paper that size analysis alone of a series of samples along a river can lead to recognition of the mineral size introduced by a tributary stream. This technique, when combined with a quantitative knowledge of the rate of fade of heavy mineral characteristics with distance along a river, may lead to a useful prospecting method.

SUMMARY

It has been generally accepted that the factor which controlled the size distribution of heavy minerals in a waterlaid sediment was fluvial sorting. The apparently sympathetic variation of heavy mineral size with light mineral size was believed to be because both were deposited simultaneously by the same current, eddy or whirl. This led to the concept of Hydraulic Equivalence based on Stokes' Law of settling rates. Mineral grains were hydraulicly equivalent when they had the same theoretical settling velocity according to Stokes' Law. Quartz was taken as standard. The hydraulic ratio was a comparison of the quantity of a mineral with the quantity of quartz of equivalent size.

Several investigations indicated that this theory did not entirely explain the facts.

A series of samples from Kenieba in Mali showed the size distribution of heavy minerals to be independant of the size of the light minerals with which they occurred and yet they were evidently sorted relative to the source rock distribution.

The theory developed to explain this situation is as follows: The heavy mineral sizes which are concentrated and which are therefore most abundant are only slightly smaller than the lag sizes and are not readily moved. The availability at one point in the stream depends on the maximum competence of the stream up to that point. In this way availability and, therefore, the size

distribution tend to remain constant along any stretch of a stream. Local sorting has no effect on the size distribution of the heavy minerals because they are only just moveable and in this respect behave more like lag sizes. They are also like lag sizes in that they become concentrated at depth by continuing scouring of the river bed. (Addendum 5) The evidence for this is mostly indirect as there has been little systematic sampling at different depths.

Samples were treated in the field by panning separately each phi size. These were recombined before final separation into the sizes shown in the cumulative curves. The percentage by volume of heavy mineral in each size was estimated visually. Laboratory work has since confirmed the validity of this estimation.

The presence of drift sizes, which are normally absent, seems to indicate the proximity of a source. At distances of about seven kilometres it may be possible to detect heavy mineral sources with samples taken near stream confluences, but the evidence was not conclusive.

The theory evolved to explain the data from Kenieba was found to be equally capable of explaining the data originally used to justify the concept of hydraulic equivalence.

Future work will involve testing the theory put forward in this paper in many different kinds of stream. It will also be necessary to confirm the concentration of lag and drag size with depth by systematic sampling. Much of this might be done in laboratory flumes. A great deal of sampling and analysis will have to be done before the suggestions put forward in this paper for the long distance detection of source rocks can be properly evaluated.

ADDENDA

ADDENDUM 1

Treatment of Samples

In the field samples, usually of five litres, were first separated into the following sizes: 10, 6, 4, 2, 1, ½, ¼ mm. The three largest sizes were inspected for heavy mineral grains. The other sizes were panned. The concentrate was then recombined and the tailings measured for volume. After the heavy mineral concentrate was dry it was screened into sizes of: 2, 1, 0.59, 0.42, 0.25 and 0.11 mm. The volume in each size was measured in a graduated cylinder and a visual estimate, based on color, was made of the proportion of quartz left in the sample. Twenty three samples, numbers 500 to 522 were retreated and measured in the laboratory. Treatment was as follows:

Samples were split into two fractions with a microsplitter. (One sample, 502, considerably larger than the rest was split into four.)

Each split sample was separated into the following sizes by screening for one minute on a mechanical shaker: +0.25, +0.177, +0.125, +0.088, -0.088 mm.

These fractions were then treated for separation of the light minerals. For this a superpanner was used. This is a temperamental device which is nevertheless probably quicker for achieving a reasonable separation of light minerals from heavy than any other method.

The sample is put at one end of a shallow V-shaped copper trough. This trough can be tilted about an axis perpendicular to its length. When the machine is in operation, the trough is agitated longitudinally and laterally. It is possible to control both the frequency and amplitude of oscillation in each direction. A trickle of water enters the end of the trough at which the sample was placed. Under the influence of the shaking and in the medium of the water flowing from one end to the other the minerals follow the direction of flow. The light minerals move first and faster and the heavy follow. Theoretically the actual flow of the water has no effect on the movement of minerals; in fact it has an important effect.

The lateral vibration is symmetrical but the longitudinal vibration is caused by an eccentric wheel in one direction, and returned by a coil spring. By varying the tension on the spring it is possible to alter the force of rebound of the trough. This has the effect of imparting to all the minerals a backward momentum. The denser minerals acquire stronger momentum and are therefore forced more effectively backwards.

After a certain amount of practice it is possible by judicious use of the controls to achieve a reasonably good separation of the heavy minerals in a sample every fifteen minutes.

Minerals are removed with the water by suction from the distal end of the trough. The two fractions are filtered and dried. In each case the light mineral fraction was preserved as separation was never perfect and the division was usually made after a few grains of heavy minerals had passed over. Although no use of the light fraction is foreseen, they are kept lest it ever become necessary to search for a mineral of marginal density. It is also conceivable that the sand itself contains useful information.

Although the superpanner is intended for use with a continuous flow of water from one end of the trough to the other an adaptation of this was found to be rather more effective. By control of the outflow of water and of the slope of the trough it was possible to adjust the level of water in the trough so that the sample was sorted by wave action.

By the combination of wave action and slope promoting forward movement, working against the longitudinal asymmetrical oscillation promoting backward movement, the two mineral fractions could sometimes be induced to proceed in opposite directions. The relation between the two methods is very much as a fluvial placer is to a marine placer. The second way is far the most effective but the trough is not designed for filling and this rather more refined approach would, ideally, require a method of keeping the two oscillators in phase.

ADDENDUM 2

Weighing

The mineral quantities were measured by weight rather than by volume for three reasons. (1) Measurement by weight seems the more commonly used method, making comparisions easier. (2) Volume measurements would involve transferring the sample from one container to another and back. Several grains are lost at each step and this might be significant for the smaller sizes. (3) No suitable measuring container was available. It would have to have been adequate for measuring both as much as 50 ccs. and as little as 0.5 ccs. and, in the latter case to two places of decimals.

After drying, each separate size fraction was put in a paper packet. It seemed that the finer sizes adhered to the surface of any packet, whether of paper or polythene. In order to save time and so as not to lose what might have been a significant fraction of the smaller samples, each was weighed inside its packet. Twenty five packets were weighed separately and the standard deviation calculated. The error this may introduce is discussed below.

The significance of any error in weighing can be measured in terms of its effect on the mean size.

Evidently a 10% error in the weighing of the +0.088 mm. fraction will have a greater effect on the mean than a comparable error in weighing the -0.088 mm. fraction. The first part of Figure 20 shows the effect of 50%, 100% and 200% errors in the -0.088 mm. fraction of a typical curve. The mean size does not vary greatly. The probability of errors of this order were calculated using the standard deviation and the frequency with which sufficiently low values occurred in the weighings made.

In the second part of the figure similar plots are shown for 50% and 100% errors in the 0.088 mm. fraction. Evidently they have a greater effect on the mean size but the probability of such errors happening is much less as the quantities of minerals in these size grades is greater. For instance, for a 100% error the packet would have to be different from the mean weight to the extent of over two standard deviations. This is unlikely.

In the light of these considerations it seems that the chances of the mean size measurements being seriously effected by variations in the packet weight can be ignored.

Calculation of probability

One standard deviation from the mean packet weight is 0.2147 grams. There is therefore a 95% probability that the packet will be within 0.42 grams of the mean. In 100 measurements the probability of having packets which weigh 0.42 gms or more different from the mean is 5%. There were 110 measurements. The probability can still be taken at 5%.

The probability that one such packet will occur in any one sample is 5/100.

In order for a packet which was 0.42 gms. different from the mean to make a difference of 200% to the sample weight the sample would have to weigh less than 0.21 gms. Now there is only one sample sufficiently small so that probability of a 200% change is

$$5/100 \times 1 = 0.05$$

Similarly, for a 50% error a sample would have to weigh less than 0.84 gms. There are 9 such samples in the outer size fractions. The probability of this happening is

$$5/100 \times 9 = 0.45$$

Although this is by no means improbable its effect is evidently unimportant. (See Figure 20).

DIAGRAM SHOWING THE EFFECTS ON THE MEAN SIZE OF CERTAIN WEIGHING ERRORS

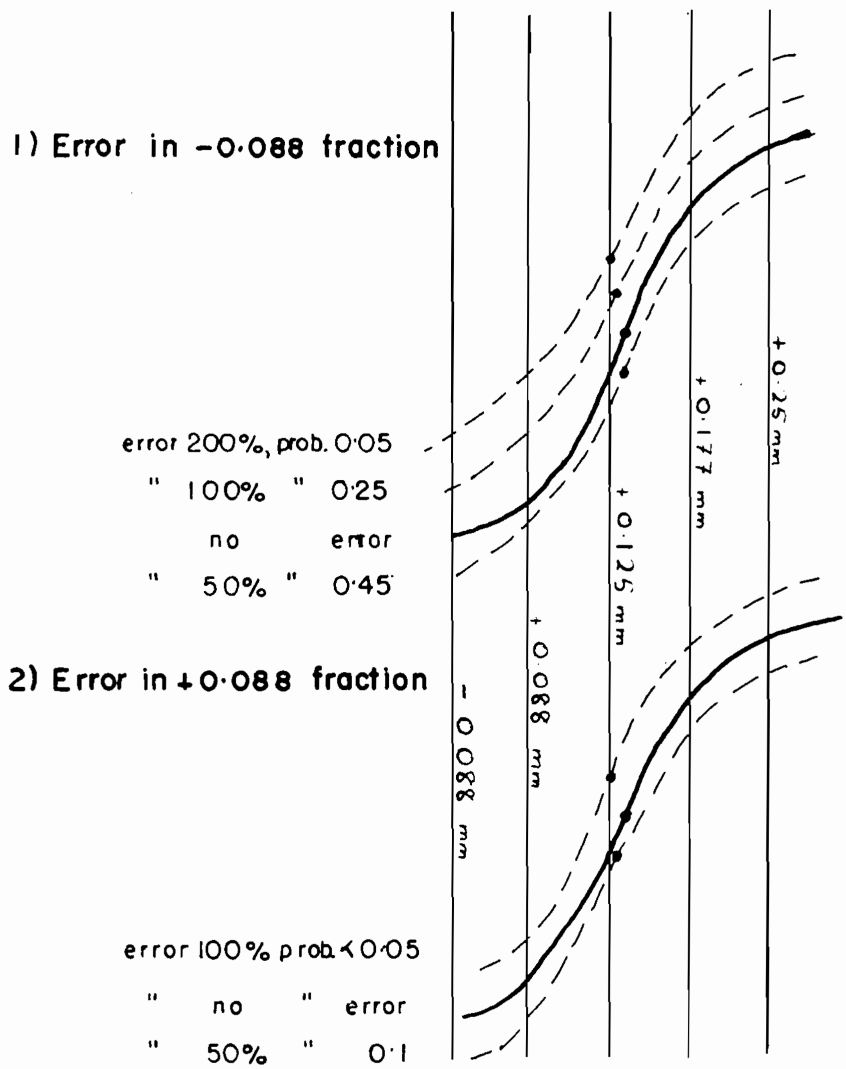


FIGURE 20

ADDENDUM 3

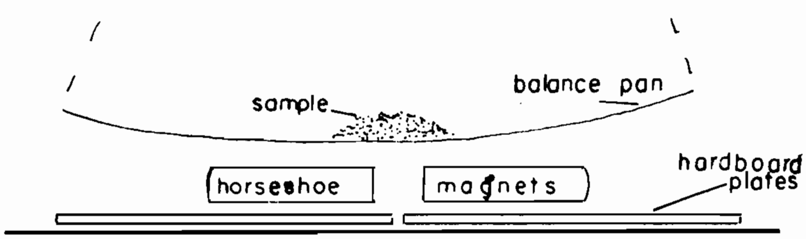
Magnetism

In the search to detect a mineralogical difference between the samples before and after the confluence an improvised way of measuring the magnetic susceptibility was tried.

This was to weigh a small quantity of the sample in question and then to reweigh the same portion within a magnetic field. Two small horsehoe magnets were used and they were put under the balance pan as shown in Figure 21. Each was attached to a hardboard plate so that it could be returned to the same position every time.

FIGURE 21

SHOWING POSITION OF MAGNETS



Between the first and second and the second and third readings the magnets were removed and the pan was tapped so that the mineral pile was rearranged. In each case the rearrangement appears to have increased the magnetic effect. This is tentatively attributed to the more forceful downward progression of the magetite and iron-rich ilmenite, both of which are relatively dense.

ADDENDUM 4

Chemical analysis by X-ray fluorescence

Between the positions of samples 502 and 503 (Figure 10) there is a confluence with a tributary draining a kimberlite pipe. The mean grain size in the first sample after the confluence (503) is much lower than in the previous sample. The difference in the proportions of the 0.088 mm. size fractions is considerable.

Accordingly, after grinding to about 200 mesh the two smallest size fraction of samples 500 to 504 were submitted to X-ray analysis for zirconium, nickel, chromium, vanadium and titanium.

As, in the time available, this part of the investigation could never have been much more than incidental to the main contentions of the paper, the analysis was run for comparison only. No standards were used.

In the limited amount of work done, conclusions are rather premature but they do point the way towards further investigations. It seems clear that in both the smallest size fractions the tributary contribution is relatively low in zircon. See Figures 23 and 24. Note also the similarity between the size distribution changes (Figure 10) and the changes in trace element ratios in Figures 25 and 26 in the first three samples. There appears to have been another tributary just before sample 500 contributing a diabasic suite of heavy minerals.

As, even after superpanning, the samples varied somewhat in their light mineral content and as an increase in zircon proportion must involve a complementary decrease in ilmenite, a count was made of the percentage of minerals that were not black and opaque. The results of this count are shown in Table 5. For estimating the proportions of black-opaque and other minerals a portion of the sample was spread over 1 mm. sq. paper and, using a binocular microscope, the number of each type of grain were counted in each of five squares.

Figure 25 with **Table 6** shows the data used for plotting Figure 23, replotted after allowing for the proportion of minerals that were not black and opaque. Similarly, Figure 26 with Table 7 shows the results of the same recalculation of the data from Figure 24. The apparently high Cr, Ni, V, Ti, of sample 503 (Figures 23 and 24) was evidently due to a low zircon proportion. (Table 3 contains no information of zircon quantity as no distinction was made, in counting, between zircon and quartz).

The ratios of chromium and nickel to titanium were plotted to avoid the effects of variations in sample fineness and in quartz and zircon proportions. Probably, chromium and nickel are substituting for titanium in the ilmenite lattice.

Both these elements are generally more abundant in kimberlite than in diabase. This is born out by analysis of a sample of kimberlite and of another from near a diabase outcrop.

The Cr/Ti and Ni/Ti ratio plots for each of the two smallest size fractions are shown in Figures 27 and 28 with Tables 8 and 9, along with ratios for diabase and kimberlite. Despite the fact that the tributary drains a kimberlite pipe seven kilometres away (Figure 11) there appears to be no significant change in these ratios, although in each case sample 503 has a higher value than those on either side. The temptation to apply statistical methods to measure the significance of these variations has been avoided as the geological complications are too many.

There is, for instance, the upward trend from sample 500 downstream of both grain size and Cr/Ti and Ni/Ti ratios. This may be due to reassertion of main stream characteristics after interuption by a tributary. Allmeasurements of Cr and Ni are higher than one would expect for a stream draining only dolerite. In view of this it may be significant that some + 1 mm. grains of ilmenite identified as "possibly kimberlitic" were found in the main stream about a kilometre above sample 500. This suggests that both main stream and and tributary are draining kimberlites.

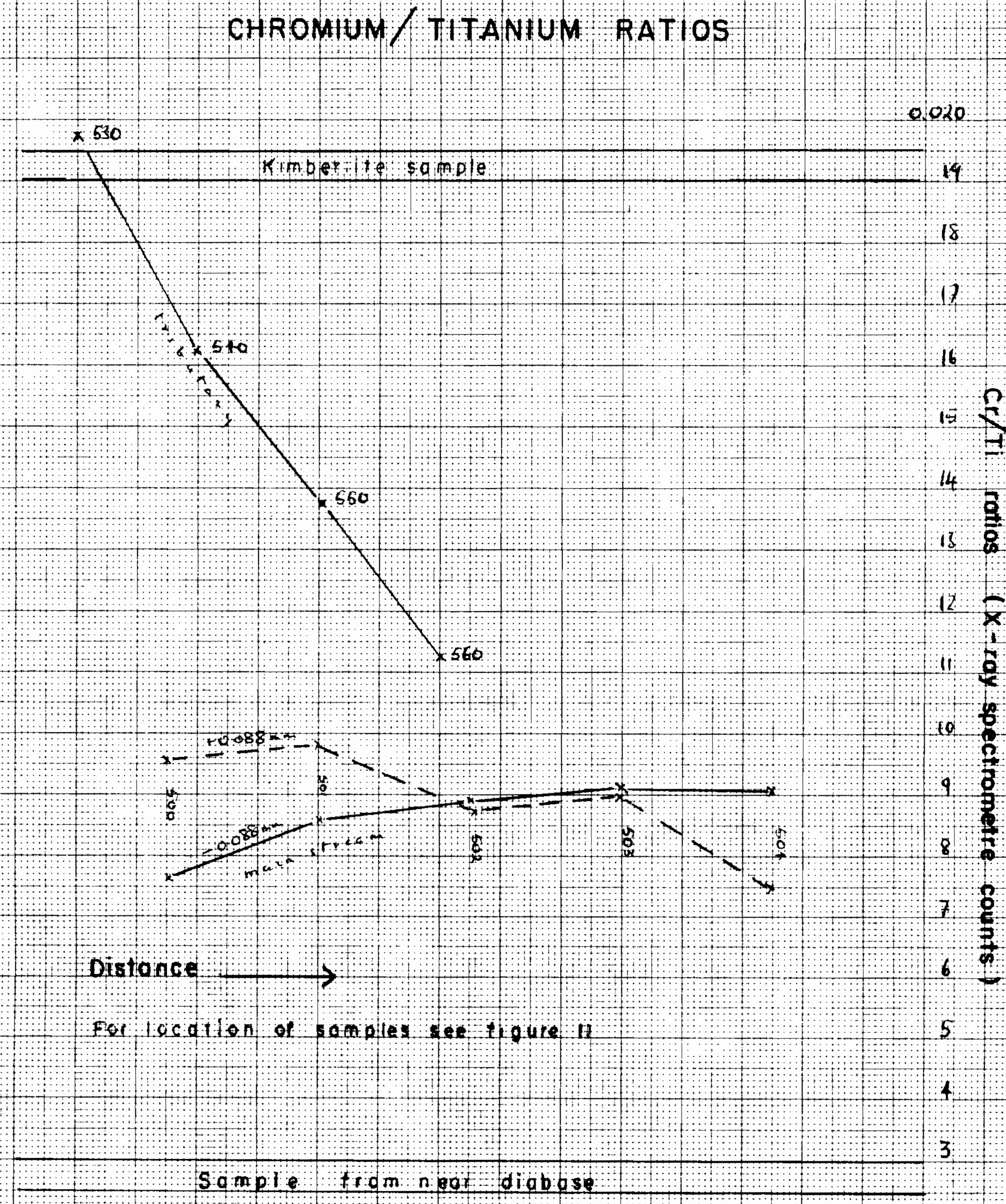
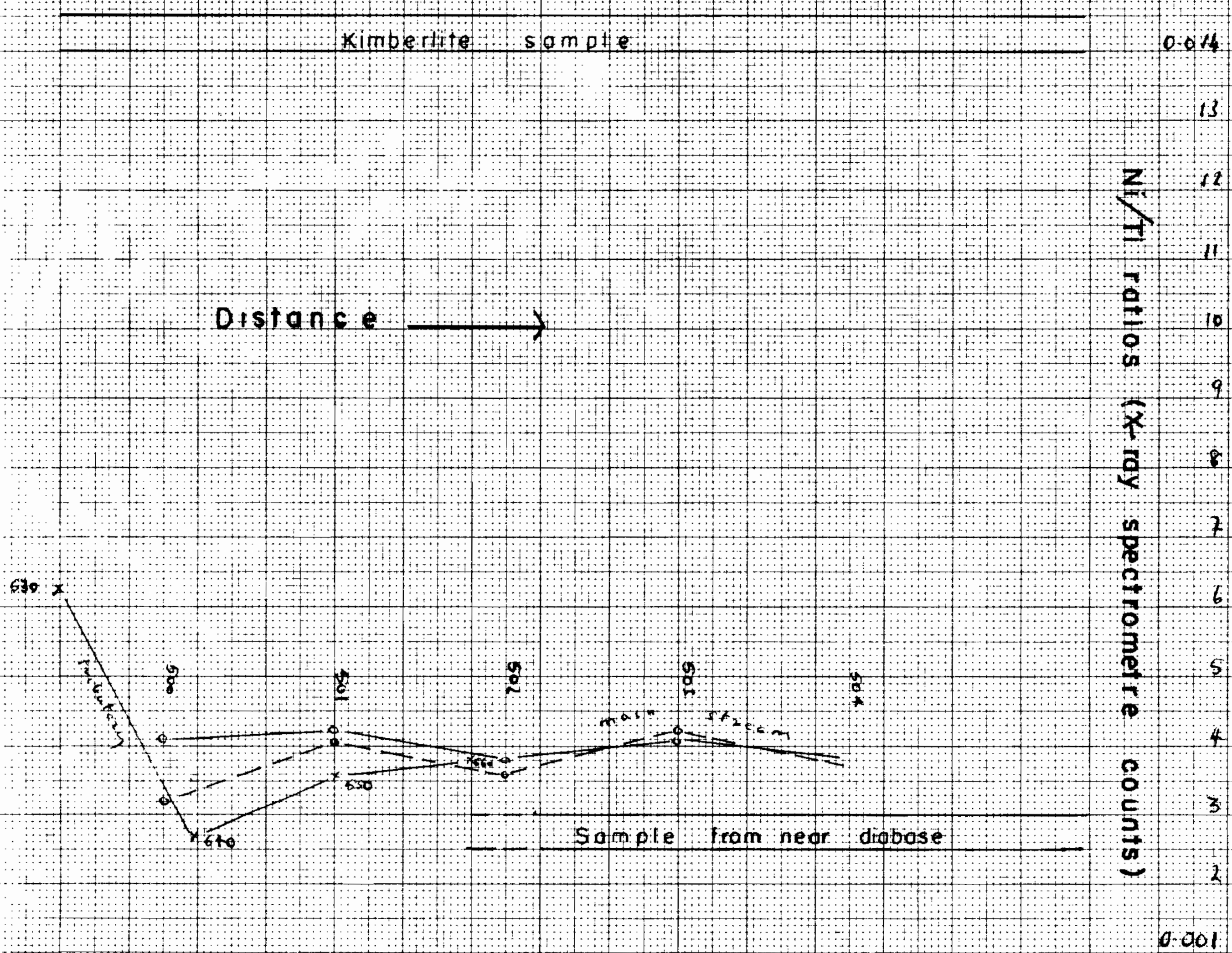

CHROMIUM / TITANIUM RATIOS
0.020
530
Kimberlite sample
540
560
560
Cr/Ti ratios (X-ray spectrometre counts)
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
500
501
502
503
504
Distance
For location of samples see figure 11
Sample from near diabase
0.001

FIGURE 27

NICKEL/TITANIUM RATIOS



For location of samples see figure 11

FIGURE 28

Also shown in Figures 27 and 28 are the values (Table 8) of four samples from the tributary. Their positions are shown on Figure 11. The stream was stagnant near the headwaters and heavy minerals were not abundant. Each of these four samples is a composite sample made by combining ten consecutive samples taken at 100 meter intervals.

No size separation was made for these four samples and because of this both lag and drag sizes were measured together. In these circumstances one would expect a much greater dilution of whatever characteristics were prevalent at the source. This appears to be confirmed by the Ni/Ti values as the ratios decrease rapidly to almost those of diabase. Yet the answer cannot be as simple as this as the Cr/Ti values are much more persistant. Also, the nickel ratios appear to be generally more eratic than the chromium ones.

Here we reach the realm of idle speculation, but indicative of the kind of problem future work will have to cope with it is perhaps appropriate to consider a possibility. Perhaps the nickel and chromium are separately concentrated on either size of the ilmenite - ulvo-spinel solvus so that they occur in different exsolution lamelli. If this were the case it is conceivable that upon fragmentation one of them would not be as easily transported or as durable as the other. Hence the disparity in persistence.

ADDENDUM 5

Concentration

"Concentration" appears frequently in this text and in discussions on heavy mineral sorting and transport. It is generally used in a sense which transends the accepted definition. It would be premature, however, to redefine it.

"Concentration" refers to the increase in quantity of one type of size of particle relative to others. In this way "increasing concentration of heavy minerals with depth" refers to the greater abundance of heavy minerals with depth relative to light minerals. When: "the drag sizes are concentrated" the reference is to the concentration of one size of heavy mineral relative to others.

Concentration of one size relative to others has been a major theme in this paper. But the concentration of lag sizes with depth has not been treated so thoroughly because it is more generally understood.

A particle of lag size is, by definition, immoveable. This is true both when the stream is flowing gently and when it is eroding its bed. On erosion of the bed on which it rests a grain of lag size becomes lowered because of its immoveability. Several writer, Tyrell (1912) and Lindgren (1911) among them have given accounts of the consequences of lowering of lag sizes in the formation of placer deposits.

Haggard (pers. comm.) points out that the frequency with which the soft material beneath the bed of the stream is disturbed by scouring is inversely proportional to its distance below the stream bed. Any scouring action must lower a particle of lag size in the zone of disturbance down to the lowest level of scour. Even though the frequency of such disturbances decreases with depth there must be an increase in the abundance of lag sizes with depth as each disturbance takes down with it all that had been left by scouring at shallower levels. Haggard argues therefore that the greatest concentration of lag sizes is at the depth of maximum scour which, for a graded stream, will be at the contact between alluvium and soft "bedrock".

In a paper on macroturbulence Matthes (1947) has thrown a lot of light on one aspect of scouring. It is instructive to reflect on what will happen to an immoveable grain in the path of one of the "kolks" shown in Figure 29.

There is a characteristic kind of concentration that occurs during the erosional lowering of a land surface. When this happens (no renewal of heavy mineral supply assumed) the smaller mineral grains are preferentially removed leaving the larger relatively concentrated. This type of concentration is distinct from stream concentration in that there is no upper limit to the weight of the grains which become concentrated. The heavier the grain the more it is concentrated by this type of process (called "deflation concentration").

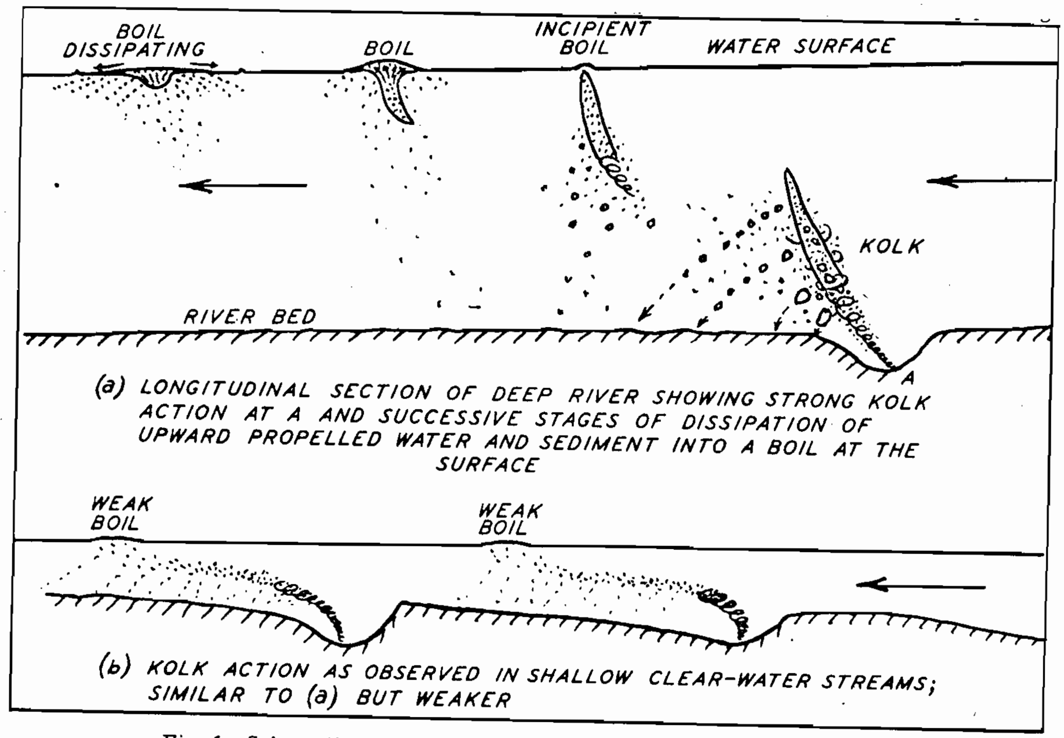


Fig. 1--Schematic representation of kolk action in sandy-bed streams

FIGURE 29 (Matthes,1947)

It is important to remember that the process of removal forms an essential part of the process of concentration. Heavy minerals are concentrated by the removal of other minerals or of other sizes. Continuing deflation concentration leads to the removal of heavier and heavier grains until the lighter grains of what was originally concentrated are themselves removed. Paradoxically then, the ultimate in the process of concentration is complete removal.

ADDENDUM 6

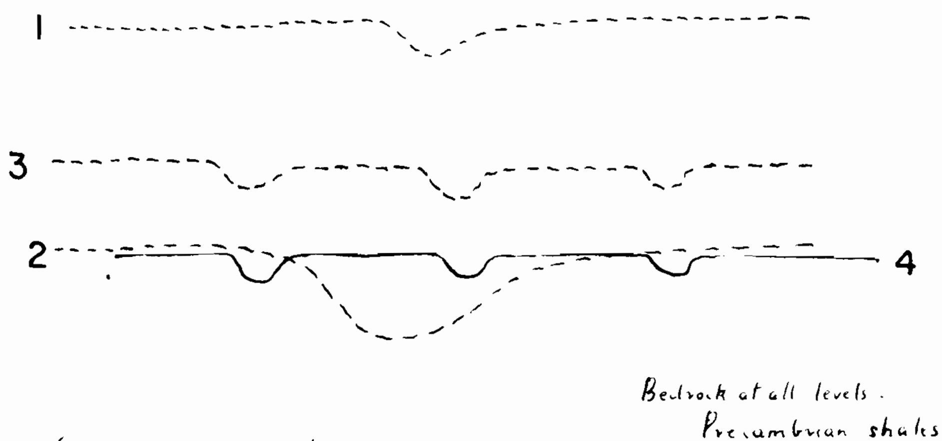
Geomorphology

The peculiar characteristics of the rivers in this region need explanation. An interpretation of the history of aggradation and degradation of these rivers is shown in Figure 30 below.

The initial stage was an easterly drainage at the level of the plateau (1). The retreat of the scarp (Figure 4) was followed by a westerly flow at a level below the present (2). There followed aggradation, probably because of climatic change. During aggradation the river meandered on an expanded floodplain. Lateritization, by cementing the alluvium had the effect of inhibiting changes in the channel pattern. Consequently degradation took place within these same meandering channels. Today's situation (4) is one of continuing degradation but as the meandering river no longer follows the course it had when it was at its lowest level, it is eroding into bedrock wherever it impinges what used to be the valley sides.

Chemical decay is active and most of the bedrock, by the time it is exposed for erosion by the stream, has been decomposed to particles of clay size. What remains at outcrops in the channel are fragments hardened by lateritization, lateritic concretions and vein quartz. The stream has no

CROSS SECTIONS SHOWING SUCCESSIVE STREAM LEVELS



1 Stream at high level
2 Stream after degradation
3 Stream meandering after aggradation
4 Present stream, after down cutting from level 3

FIGURE 30

detectable rounding effects on these fragments.

As far as the heavy mineral samples are concerned this means that any grain may have reached its present position by stream transport on higher, vanished surfaces. It also means that despite the eroded bedrock and the coarse-bedded stream the competence is very low.

Even where there is no gravel on the valley slopes to provide a source the gravels presence can still be explained without invoking a more competent stream. Although the stream may be incompetent to move heavy particles horizontally it may nevertheless be capable of influencing their downward course during degradation. The resultant direction of grain movement will then be diagonal, downward and forward, shown in Figure 31 by arrows. This diagonal direction of movement has a horizontal component. It follows that the greater the degradation the greater the horizontal distance covered by heavy particles. In this way the greater the degradation since hardrock was first eroded by the stream, the greater is the length of stream covered by gravel. Each outcrop of bedrock in the stream bed forms a "tail" of gravel forming on the downstream side. Ultimately the tails coalesce and the entire bed of the stream is covered by gravel.

A stream channel may also acquire particles of lag size residually. Similarly it may do so by the lateral migration of particles residually concentrated on the slopes bordering the stream. These processes are illustrated in Figure 32.

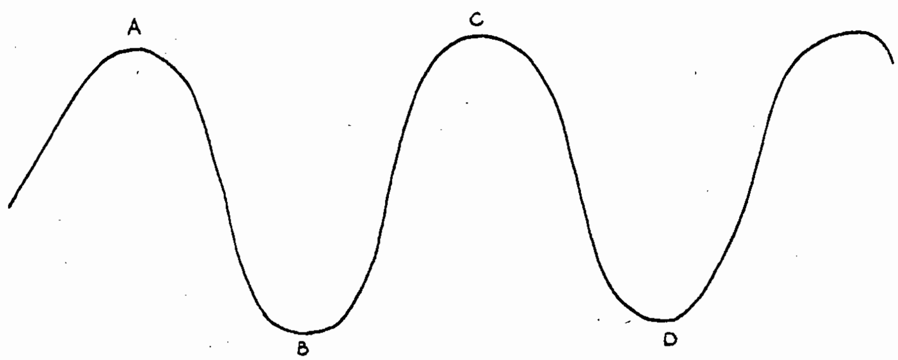
To add to the complication there has been gold digging for centuries on the plain. Gravels in many places are the tailings of gold workings. Both the gravels and the heavy minerals in them may have been moved by gold miners from several hundred yards away.

DIAGRAM SHOWING HOW THE BED OF AN INCOMPETENT STREAM MAY BECOME COVERED WITH GRAVEL

(SEE ALSO FIGURE 5)

Horizontal movement of gravel occurs only with simultaneous lowering

Plan.



Section along stream bed.

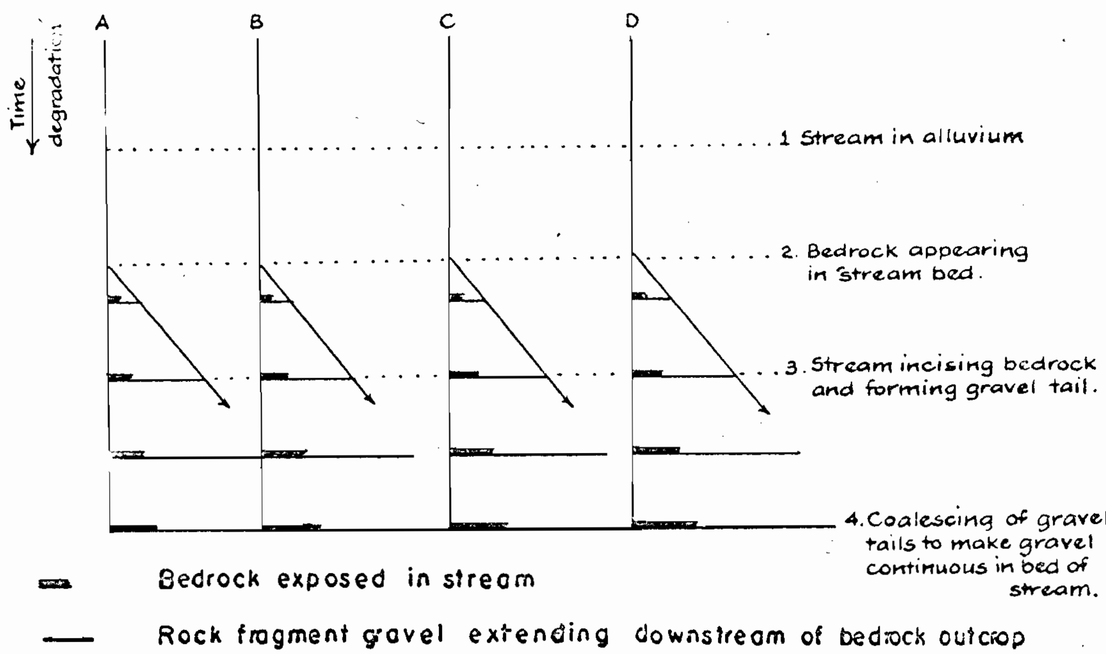
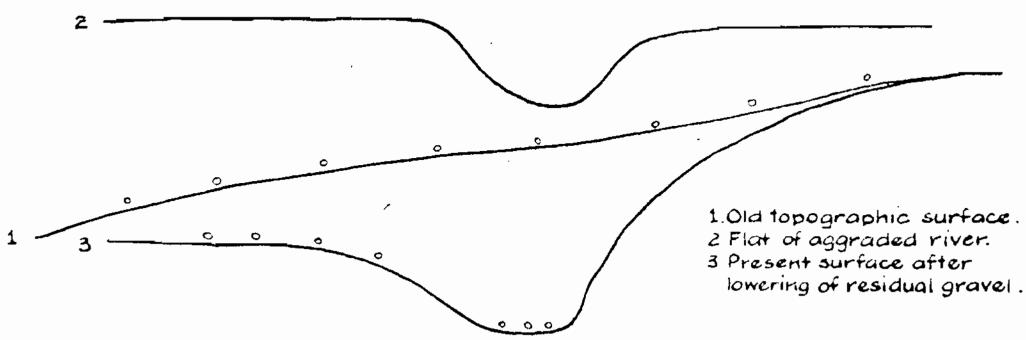


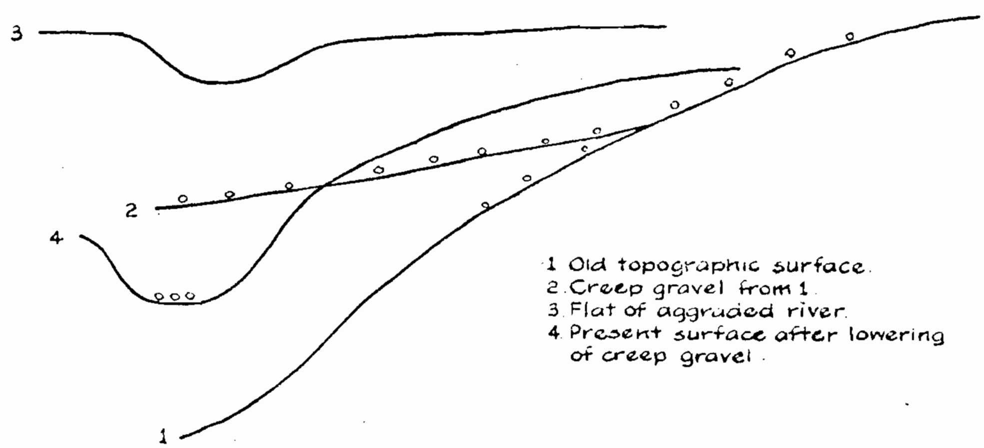
FIGURE 31

CROSS SECTIONS SHOWING HOW RIVER GRAVELS MAY BE DERIVED RESIDUALLY

Residual lowering



Lateral migration & lowering



ooo Coarse particles residually concentrated at surface

FIGURE 32

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TABLE 1

Sample fraction weights, and weights expressed as percentages of the sample.

Sample no.		+0.25	+0.177	+0.125	+0.088	-0.088
500	wt. gms.	0.788	3.126	8.896	9.549	8.023
	% wt.	3	10	29	31	26
501	wt. gms.	4.534	31.522	30.594	8.798	2.032
	% wt.	6	41	39	11	3
502	wt. gms.	5.300	23.336	18.267	5.765	1.955
	% wt.	10	43	33	10	4
503	wt. gms.	1.113	5.344	9.924	8.458	6.675
	% wt.	4	17	31	27	21
504	wt. gms.	1.580	16.798	30.982	13.558	4.278
	% wt.	2	25	46	20	6
505	wt. gms.	4.844	23.496	31.153	11.704	3.151
	% wt.	6	32	42	16	4
506	wt. gms.	4.619	23.541	43.212	20.004	4.130
	% wt.	5	25	45	21	4
507	wt. gms.	5.723	7.217	7.669	5.407	3.437
	% wt.	19	25	26	18	12
508	wt. gms.	8.123	49.264	38.613	12.293	3.939
	% wt.	7	44	35	11	3
509	wt. gms.	0.404	1.880	2.890	2.202	1.336
	% wt.	5	22	32	25	15
510	wt. gms.	1.215	8.446	11.534	4.440	1.506
	% wt.	4	31	43	16	6
511	wt. gms.	3.117	5.581	4.463	1.586	0.639
	% wt.	20	36	29	10	4

cont.

TABLE 1 (cont.)

Sample no.		+0.25	+0.177	+0.125	+0.088	-0.088
512	wt. gms.	14.011	21.625	11.895	3.769	1.715
	% wt.	26	41	23	7	3
513	wt. gms.	7.711	16.027	13.424	5.964	2.886
	% wt.	17	35	29	13	6
514	wt. gms.	0.725	2.376	3.739	2.794	1.758
	% wt.	6	21	33	25	15
515	wt. gms.	0.254	0.851	2.152	1.612	0.371
	% wt.	5	16	41	31	7
516	wt. gms.	2.282	8.662	11.265	5.682	2.677
	% wt.	7	28	37	19	9
517	wt. gms.	2.453	5.980	3.660	0.874	0.025
	% wt.	17	46	28	7	2
518	wt. gms.	0.793	5.203	11.412	9.468	5.257
	% wt.	2	16	36	30	16
519	wt. gms.	3.443	12.595	9.378	2.215	0.813
	% wt.	12	44	33	8	3
520	wt. gms.	6.892	19.999	26.916	12.449	7.193
	% wt.	9	27	37	17	10
521	wt. gms.	5.170	9.845	11.679	7.480	5.721
	% wt.	13	25	29	19	14
522	wt. gms.	5.144	9.408	12.214	9.920	10.809
	% wt.	11	20	25	21	23

TABLE 2

Weighings with and without a magnetic field

+0.25	+0.177	+0.125	+0.088	-0.088	Grain Size / Sample Number
0.6402	1.9819	2.7067	1.8437	2.1129	
0.6785	2.0070	2.7426	1.8810	2.1503	
0.6795	2.0080	2.7443	1.8813	2.1546	500
0.6813	2.0120	2.7455	1.8819	2.1570	
411	301	388	382	441	
6.4	1.52	1.43	2.08	2.09	
2.1787	2.7354	2.3831	2.3160	1.6942	
2.2044	2.7700	2.4108	2.3494	1.7275	
2.2056	2.7725	2.4136	2.3525	1.7280	501
2.2077	2.7733	2.4136			
290	379	305	362	329	
1.33	1.39	1.28	1.56	1.94	
1.5327	2.0380	1.7410	1.1602	1.4347	
1.5543	2.0648	1.7699	1.1884	1.4691	
1.5542	2.0651	1.7694	1.1886	1.4697	502
1.5545	2.0653	1.7686		1.4707	
218	273	276	279	360	
1.42	1.34	1.58	2.40	2.51	
1.0611	1.7592	2.0607	1.7122	1.3538	
1.0877	1.7846	2.0914	1.7411	1.3827	
1.1278	1.7862	2.0933	1.7418	1.3862	503
	1.7868	2.0942	1.7436	1.3872	
667	276	335	324	334	
6.31	1.57	1.62	1.89	2.47	
1.0924	1.7246	1.8822	1.9255	1.4168	
1.1104	1.7465	1.9054	1.9586	1.4457	
1.1108	1.7482	1.9070	1.9592	1.4475	504
	1.7499	1.9080	1.9595	1.4496	
183	253	258	340	328	
1.67	1.47	1.37	1.76	2.32	

The first reading in each group is the true weight, the next three readings are the weights under the influence of a magnetic field. The fifth figure is the difference between the true weight and the greatest weight under the influence of the magnetism. The sixth figure is the percentage difference (summarized in Table 2).

TABLE 3

X-ray spectrometer average readings for the -0.088 mm. size fraction.

Sample no.	500	501	502	503	504
Zircon	12.0	15.6	15.2	12.8	17.4
Nickel	7.2	6.6	6.4	7.0	6.6
Chromium	13.4	13.6	15.0	15.8	15.8
Vanadium	169	160	173	180	186
Titanium	1728	1565	1674	1723	1743

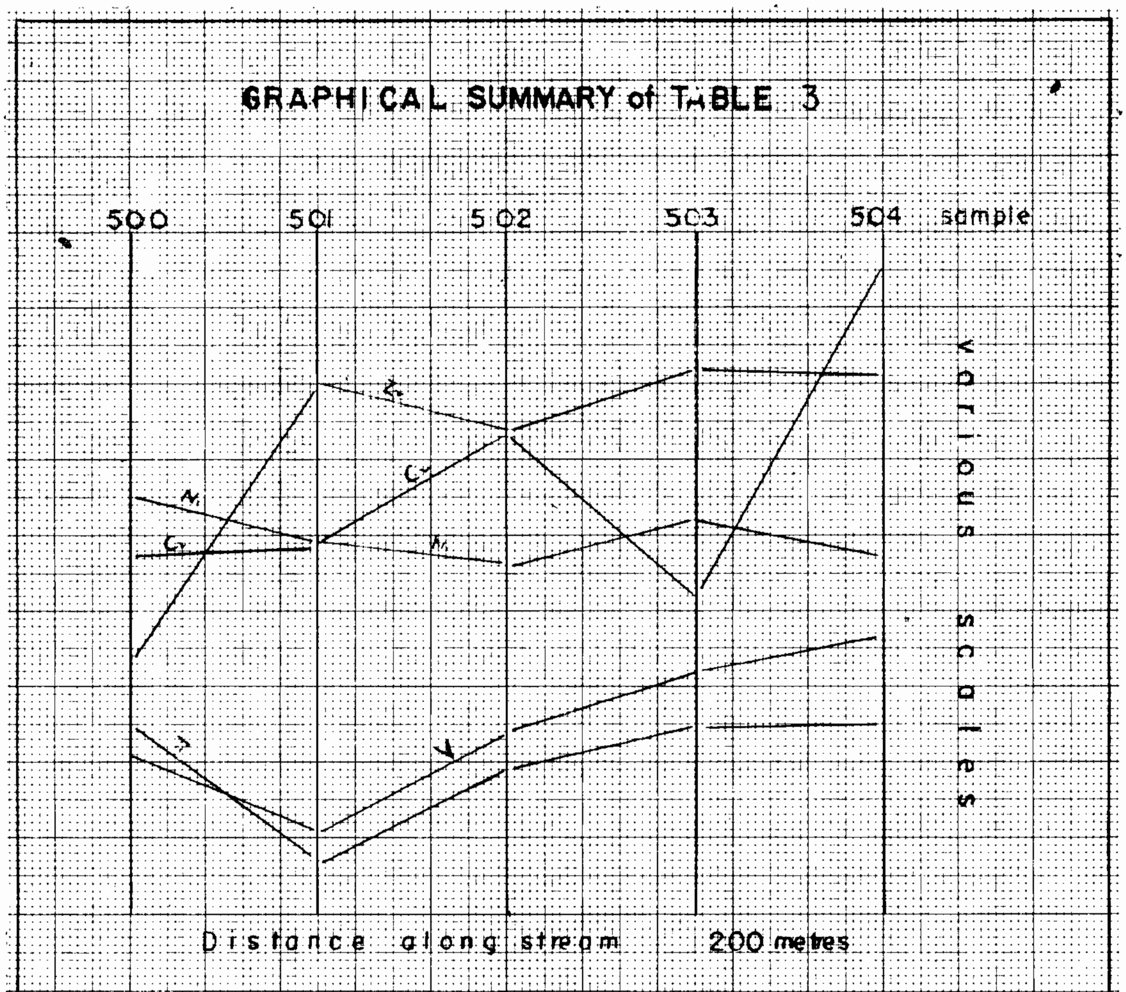


FIGURE 23

TABLE 4

X-ray spectrometer average readings for the 0.088 to 0.125 mm. size fraction.

Sample no.	500	501	502	503	504
Zircon	6.4	6.4	6.8	3.0	6.2
Nickel	4.8	6.2	6.0	7.0	6.2
Chromium	13.2	15.0	13.8	15.6	12.2
Vanadium	139	162	160	179	163
Titanium	1384	1535	1562	1715	1607

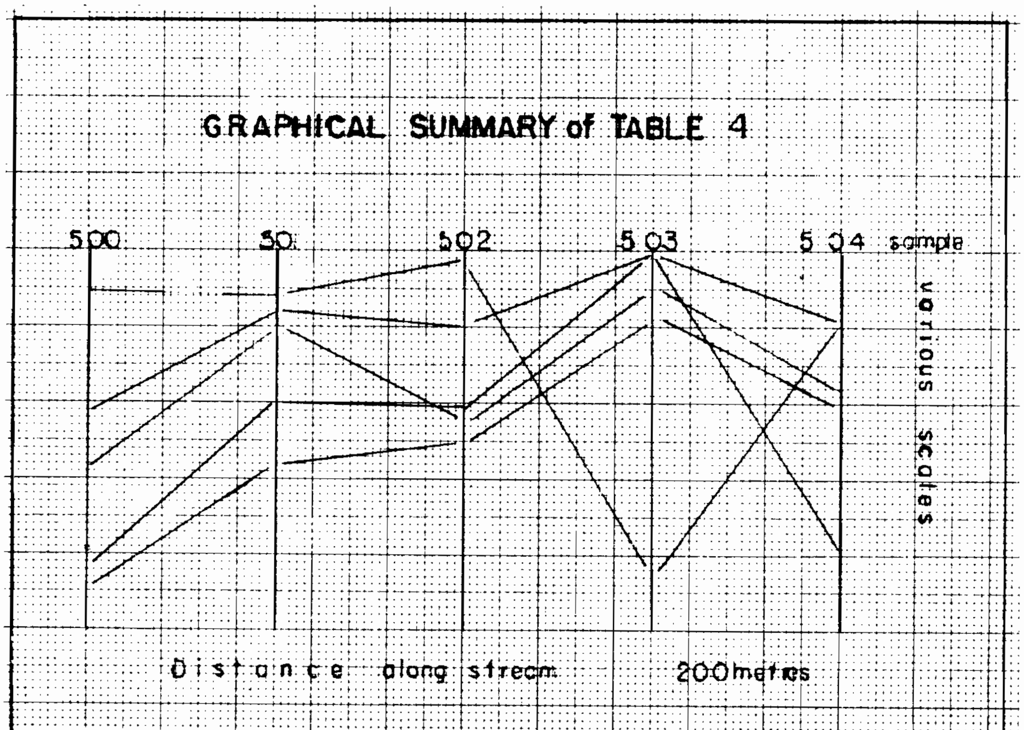


FIGURE 24

TABLE 5

Results of grain counts to measure the proportion of black-opaque minerals in each sample

Sample No.	No. grains, black-opaque	No. grains, other minerals	% other minerals	Average percent
	33	3	10	
	29	9	24	
500	44	7	14	15
	39	1	3	
	51	18	26	
	44	12	21	
	90	18	12	
501	22	4	6	15
	36	9	5	
	39	16	29	
	41	6	13	
	53	13	20	
502	51	13	20	16
	46	9	16	
	33	4	11	
	40	4	10	
	54	3	5	
503	53	9	14	10
	50	5	10	
	50	5	10	
	60	10	14	
	60	8	12	
504	40	4	11	12
	55	6	10	
	42	7	14	

Size - 0.088 mm.

Sample No.	No. grains, black-opaque	No. grains, other minerals	% other minerals	Average percent
	27	1	3	
	25	0	0	
500	30	1	3	3
	36	1	3	
	39	2	6	
	40	1	3	
	36	0	0	
501	35	2	6	2
	18	0	0	
	33	1	1	
	21	1	5	
	24	6	18	
502	33	8	19	17
	28	9	24	
	41	10	20	
	49	1	2	
	28	1	3	
503	20	0	0	4
	40	4	1	
	35	2	6	
	21	2	10	
	25	0	0	
504	28	3	9	5
	35	1	3	
	34	1	3	

Size - 0.125 to 0.088 mm.

TABLE 6

X-ray spectrometer average readings for the -0.088 mm. size fraction after correction for proportion of non black-opaque minerals.

Sample no.	500	501	502	503	504
Nickel	8.5	7.7	7.6	7.6	7.5
Chromium	15.7	16.0	17.8	17.8	17.9
Vanadium	19.9	18.8	20.6	19.9	21.1
Titanium	2038	1840	1993	1935	1980

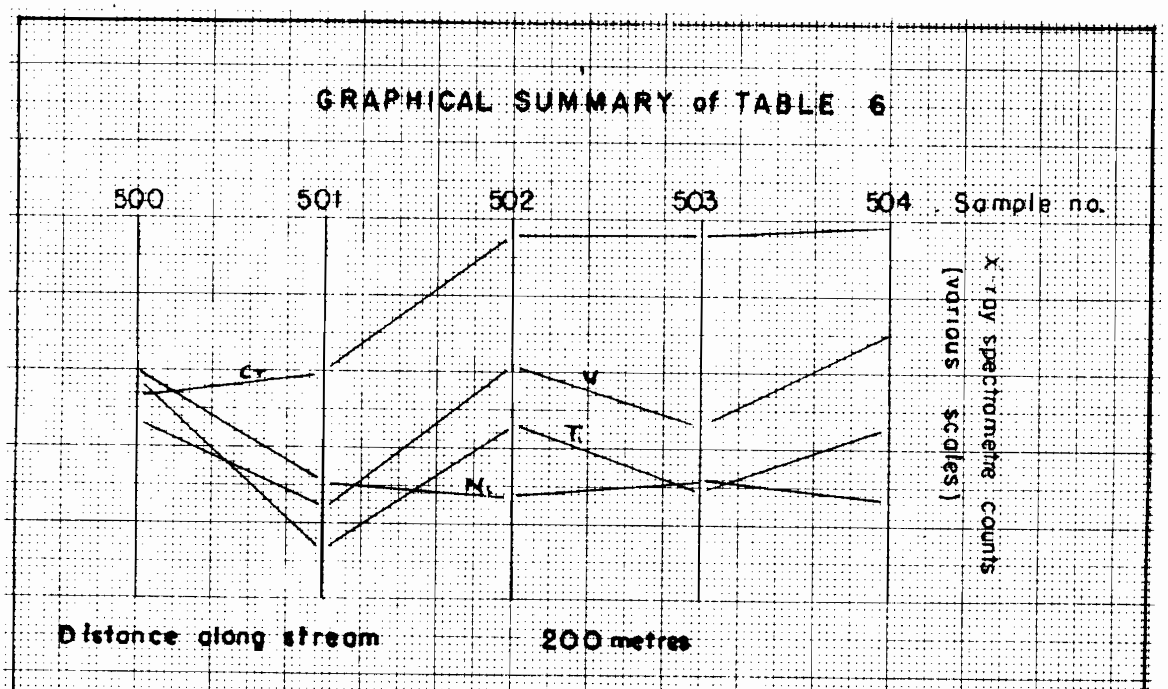


FIGURE 25

TABLE 7

X-ray spectrometer average readings for the 0.088 to 0.125 mm. fraction after correction for proportion of non black-opaque minerals.

Sample no.	500	501	502	503	504
Nickel	4.9	6.3	7.2	7.3	6.5
Chromium	13.5	15.3	16.1	16.3	12.8
Vanadium	162	165	192	187	171
Titanium	1415	1565	1880	1785	1690

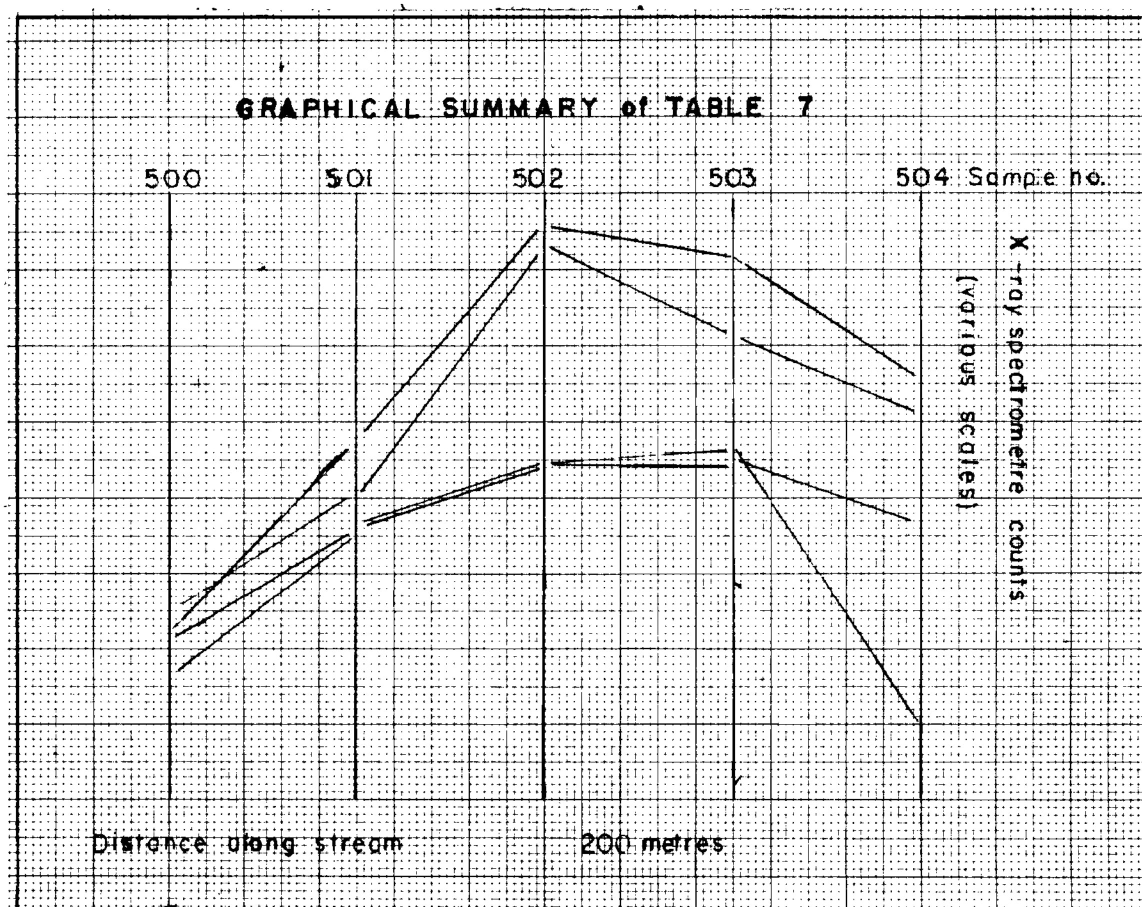


FIGURE 26

TABLE 8

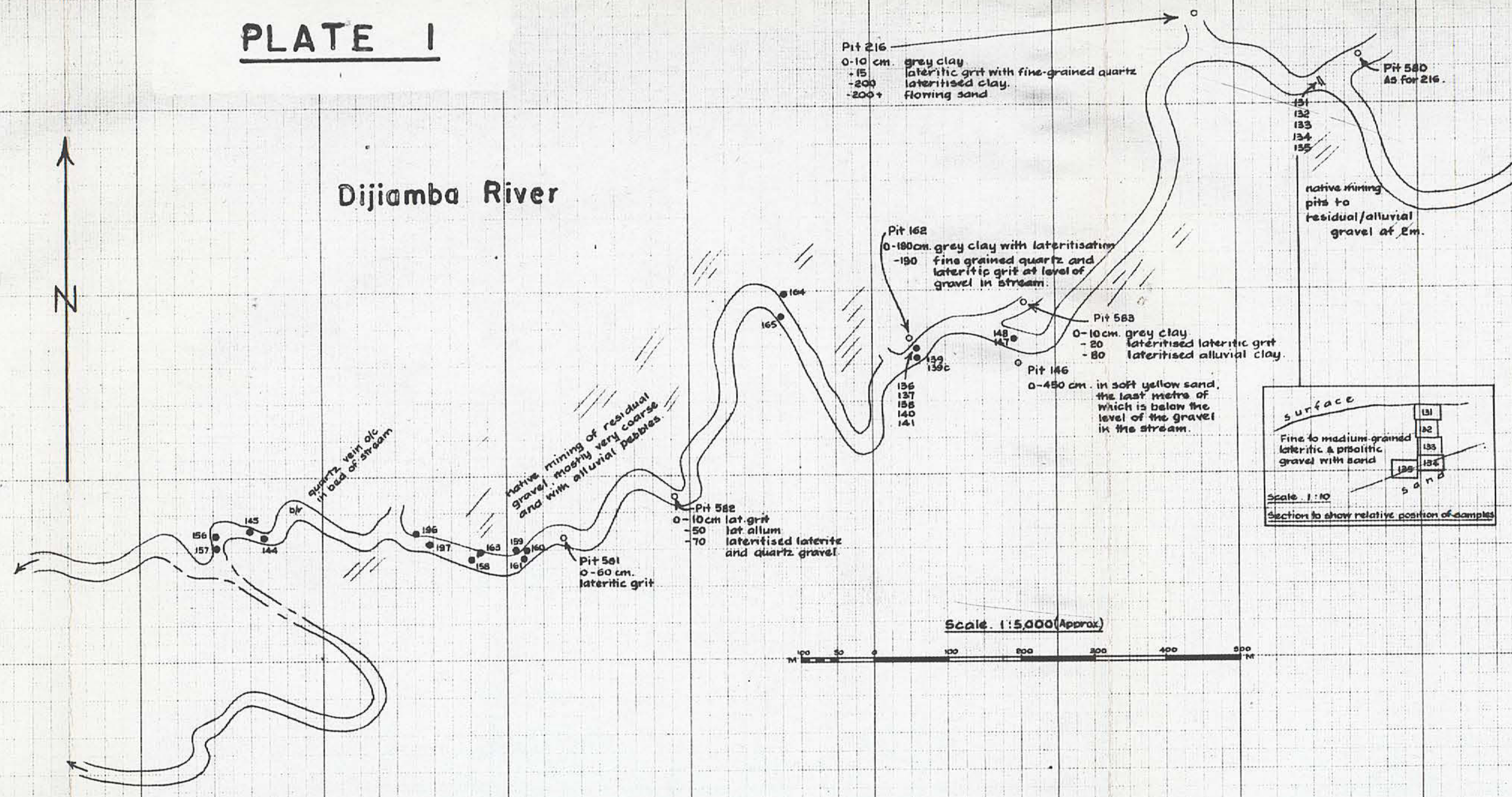
Trace element / titanium ratios

	Sample No.	Ni	Cr	Ti	Ni/Ti	Cr/Ti
Size Fraction -0.088 mm.	500	7.2	13.4	1728	.00414	.00775
	501	6.6	13.6	1565	.00421	.00868
	502	6.4	15.0	1674	.00383	.00895
	503	7.0	15.8	1723	.00405	.00914
	504	6.6	15.8	1743	.00397	.00906
Size Fraction 0.088 to 0.125mm.	500	4.8	13.2	1584	.00347	.00952
	501	6.2	15.0	1535	.00404	.00976
	502	6.0	13.8	1562	.00387	.00883
	503	7.0	15.6	1715	.00407	.00909
	504	6.2	12.2	1607	.00386	.00758
	KS3	22.8	31.0	1602	.01416	.01935
	422I	4.0	6.3	1451	.00276	.00275
All Sizes	530	7.4	23.4	1186	.00623	.01970
	540	3.2	19.2	1196	.00268	.01607
	550	4.8	18.4	1331	.00369	.01381
	560	5.0	14.8	1302	.00384	.01121

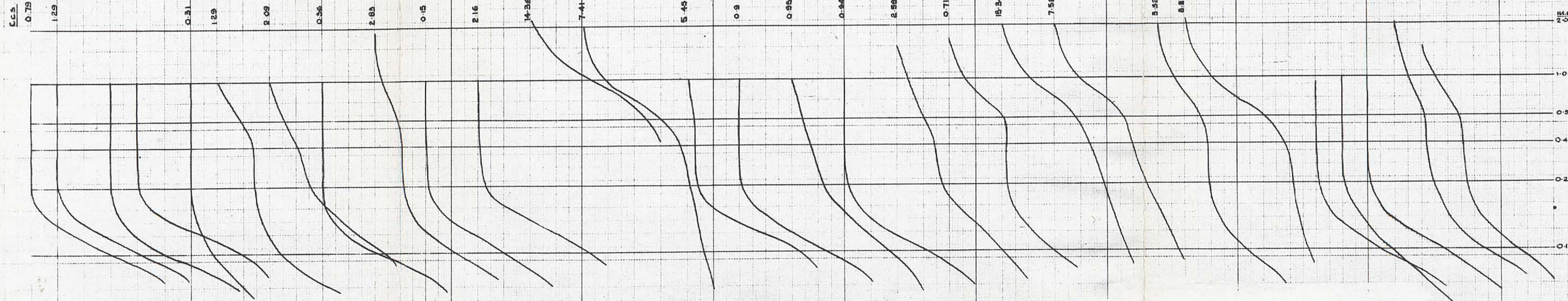
PLATE I

Sample No.	∠0·11	0·11	0·25	0·42	0·59	1	2	4
	millimetres / ccs. or grains							
156	0·28	0·51	Tr.	Tr.	Tr.	6gr.	–	–
157	0·48	0·81	Tr.	Tr.	Tr.	4gr.	–	–
145	0·56	0·34	Tr.	Tr.	Tr.	4gr.	–	–
144	0·35	1·32	Tr.	Tr.	Tr.	5gr.	–	–
196	0·25	0·06	Tr.	Tr.	Tr.	–	–	–
199	0·64	0·3	Tr.	0·1	0·25	0·05	–	–
158	0·25	1·19	0·2	0·2	0·25	33gr.	–	–
143	0·2	0·16	Tr.	Tr.	Tr.	2gr.	–	–
159	0·9	1·28	0·07	0·09	0·35	0·16	1gr.	–
140	0·06	0·59	Tr.	Tr.	Tr.	3gr.	–	–
161	0·28	1·78	0·1	Tr.	Tr.	3gr.	–	–
164	0·58	Tr.	0·1	1·4	6·25	6·15	0·4	–
165	0·55	0·85	0·7	Tr.	Tr.	18gr.	1gr.	–
162	0·58	4·3	0·1	0·07	0·2	0·1	–	–
136	0·27	0·53	Tr.	Tr.	Tr.	10gr.	–	–
137	0·21	0·49	0·1	0·05	0·1	7gr.	–	–
138	0·24	0·48	Tr.	Tr.	Tr.	2gr.	–	–
140	0·49	1·3	0·2	0·2	0·4	0·1	–	–
147	0·15	0·3	Tr.	0·1	0·5	0·1	–	–
139	0·84	2·70	1·36	1·20	5·22	3·42	0·1	–
139c	0·28	1·92	0·84	0·42	2·62	1·44	5gr.	–
148	1·08	0·95	0·06	0·12	0·7	0·4	1gr.	–
147	0·68	0·85	0·54	1·3	3·7	1·6	0·2	–
216	0·64	0·2	Tr.	–	–	–	–	–
131	0·30	0·28	Tr.	Tr.	Tr.	3gr.	–	–
132	0·32	0·18	Tr.	Tr.	Tr.	4gr.	–	–
133	0·32	0·56	Tr.	Tr.	Tr.	22gr.	–	–
134	0·75	0·92	0·05	0·05	0·3	0·2	2gr.	–
135	0·49	0·6	0·05	0·05	0·3	0·15	–	–

Dijiamba River



Ccs.		Sample No
0·79	Gravel at 20cm. best in pit to 1·0m. Fine, light lat.	156
1·29	Best surface gravel in stream bed. Fine grained light laterite.	157
	Coarse to medium grained angular quartz gravel.	145
	ditto.	144
0·31	Gravel from pit just inside sharp bend in channel. Fine gravel laterite.	196
1·29	Gravel from stream bed. Mostly lateritic.	197
2·09	Coarse quartz gravel from stream bed.	158
0·36	Lateritic grit o/c in channel wall.	143
2·83	Very coarse quartz gravel in stream bed but evidently derived residually from above.	159
0·15	Gravel from fine to medium grained shoal hard by 159.	160
2·16	ditto.	161
14·38	Very coarse grained quartz and rich frag. gravel from channel through intensive gold mining.	164
7·41	ditto.	165
5·45	Thin band of very fine grained quartz gravel from pit beside channel. Recovered from same horizon as coarse gravel in channel.	162
0·9	Coarse to medium quartz and rock fragment gravel from gold tailings.	136
0·95	ditto	137
0·94	ditto	138
2·59	ditto	140
0·71	ditto	141
15·34	ditto	139
7·52	ditto	139c
3·32	ditto	148
8·87	ditto	147
	A series of samples taken at different levels in the same part of a shoal of fine-grained gravel in the stream bed.	131, 132, 133, 134, 135

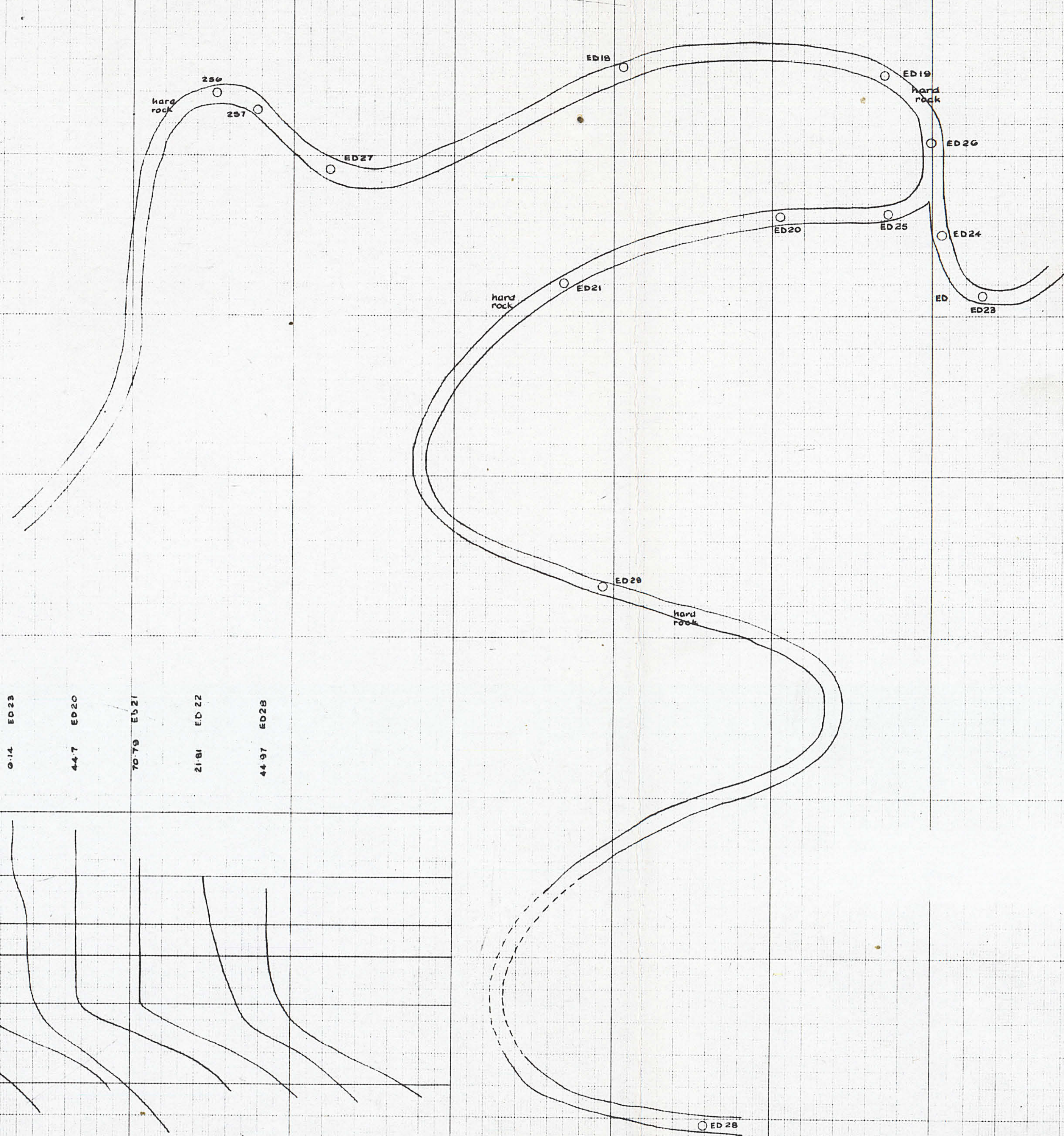


Cumulative Curves

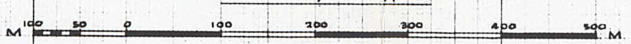
PLATE 2

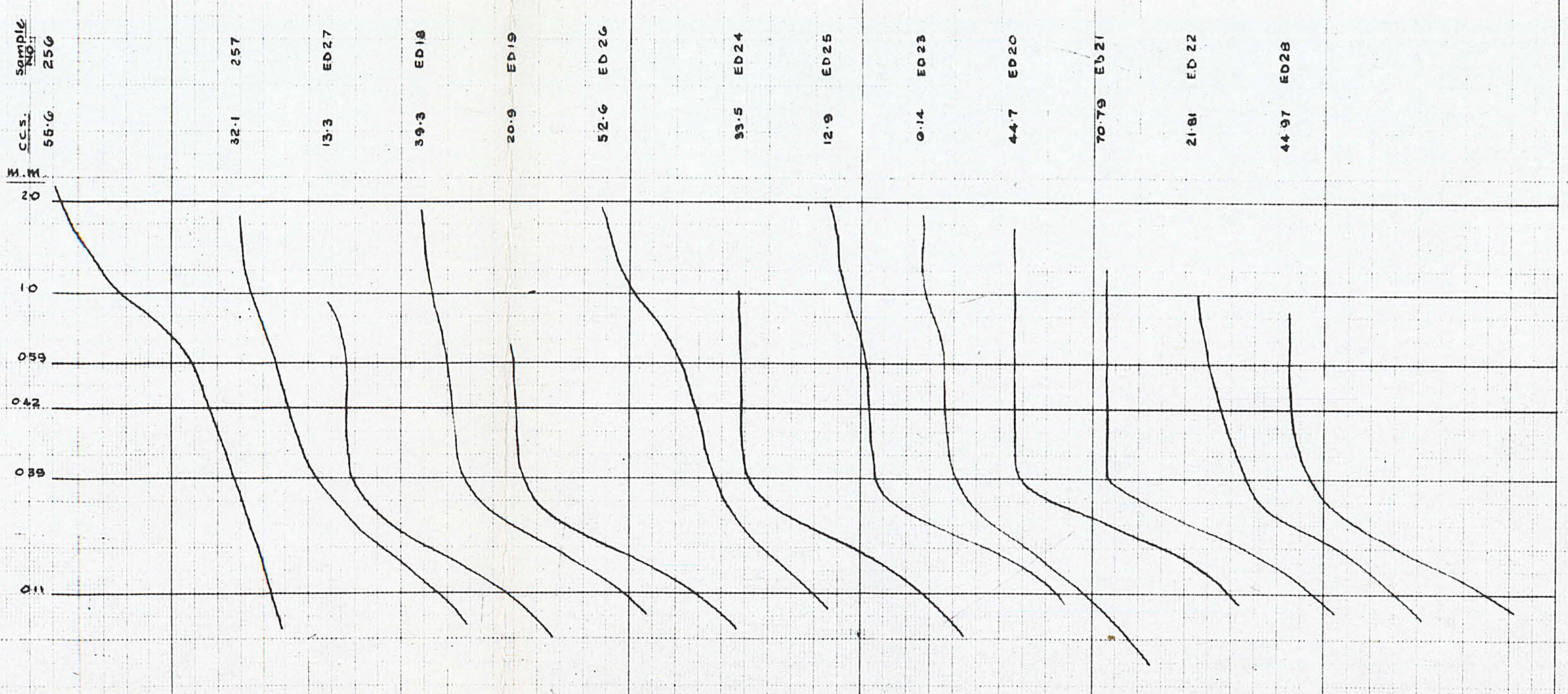
DATA								
Sample No.	<0·11	0·11	0·25	0·42	0·59	1	2	4
	millimetres							
	ccs. or grains							
256	3·96	9·85	4·75	4·3	17·2	14·0	1·6	-
257	2·94	17·7	4·4	1·02	3·8	1·6	Tr.	-
ED 27	3·05	8·95	0·32	0·05	1·0	8gr.	-	-
ED 18	3·85	2·95	2·48	0·7	2·88	1·9	4gr.	-
ED 19	3·6	15·8	0·54	0·3	0·45	0·1	-	-
ED 26	3·73	22·5	4·33	3·65	10·7	6·8	0·5	-
ED 24	5·45	26·7	0·94	0·15	0·25	0·05	-	-
ED 25	0·2	10·1	0·54	0·23	1·11	0·72	3gr.	-
ED 23	1·75	3·34	0·32	0·08	0·45	0·2	2gr.	-
ED 20	1·9	41·7	1·14	Tr.	Tr.	0·05	-	-
ED 21	4·86	65·4	0·54	Tr.	Tr.	1gr.	-	-
ED 22	2·82	14·6	2·08	1·24	0·85	0·3	6gr.	-
ED 28	4·42	3·63	3·97	0·11	0·09	0·08	-	-

Middle Doundi River



Scale 1:5,000 (Approx.)





Cumulative Curves

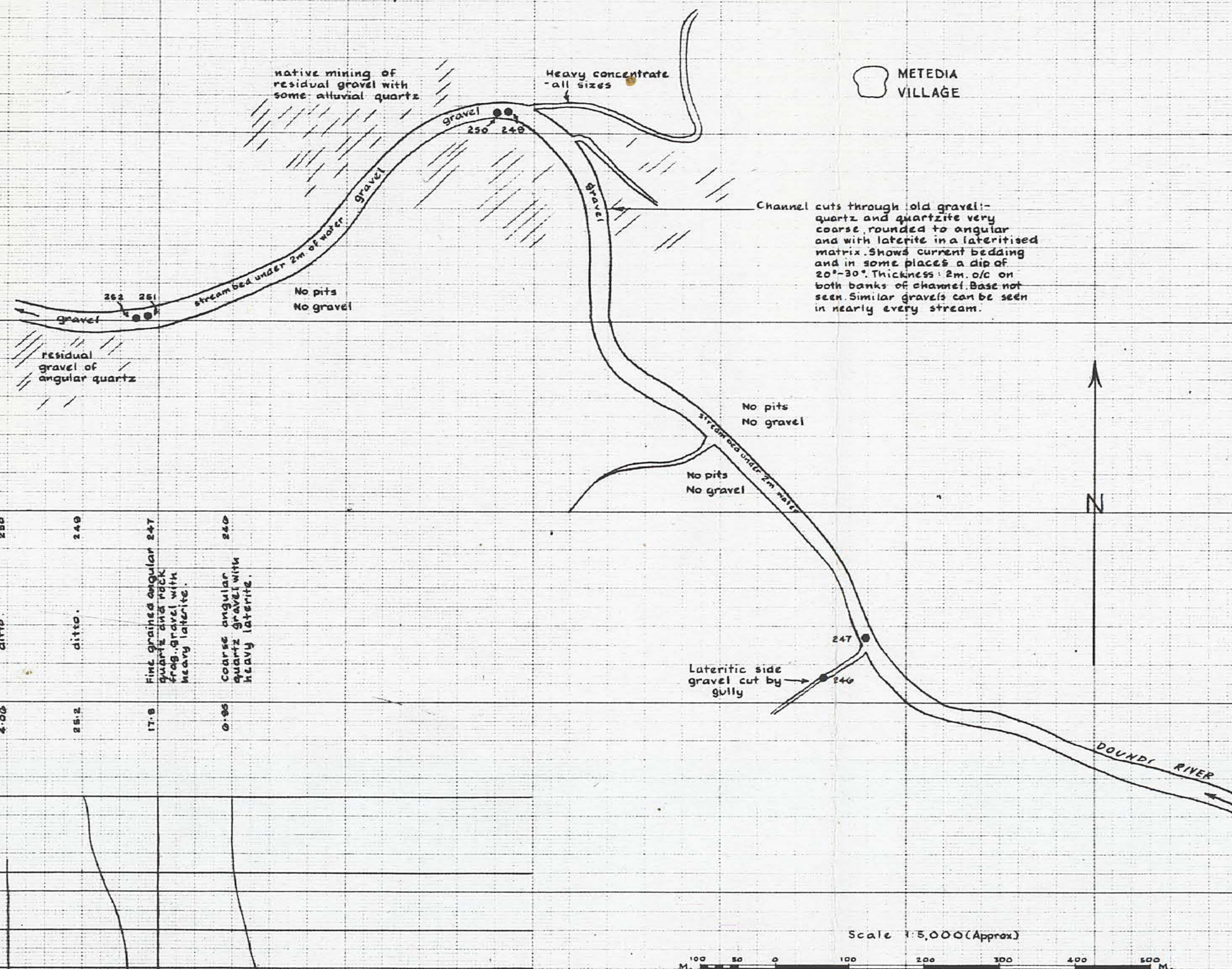
PLATE 3

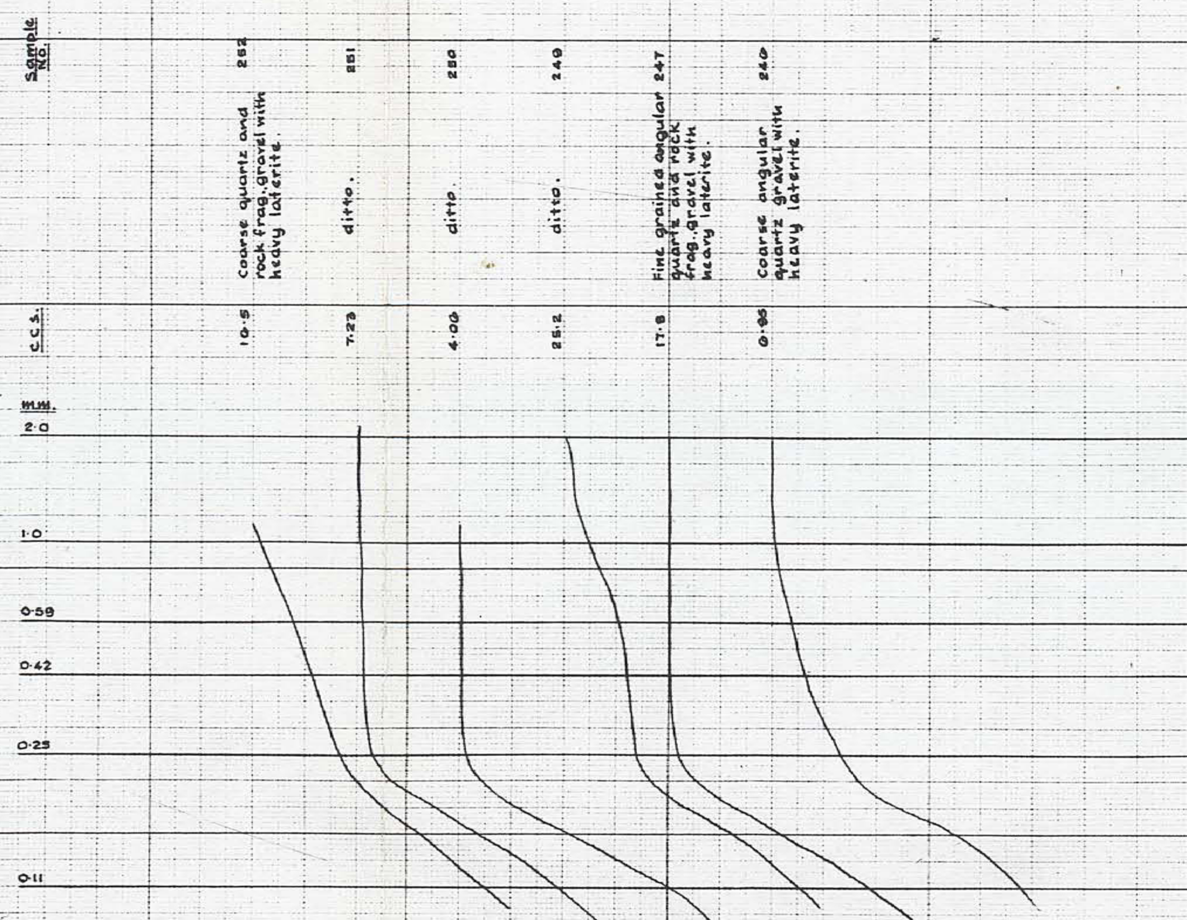
Lower-middle Doundi River

DATA

Sample No.	<0.11	0.11	0.25	0.42	0.59	1	2	4
	millimetres							
	ccs or grains							
246	0.4	4.9	0.8	0.3	0.45	0.1	–	–
247	3.60	12.3	0.46	0.15	0.2	0.1	1gr.	–
248	1.75	16.8	1.05	0.64	2.75	2.2	6gr.	–
250	7.5	32.7	0.4	Tr.	0.05	10gr.	–	–
251	1.65	5.2	0.25	0.05	0.08	12gr.	–	–
252	1.6	9.6	1.8	1.12	2.0	0.4	4gr.	–

Sketch plan from aerial photographs x 10

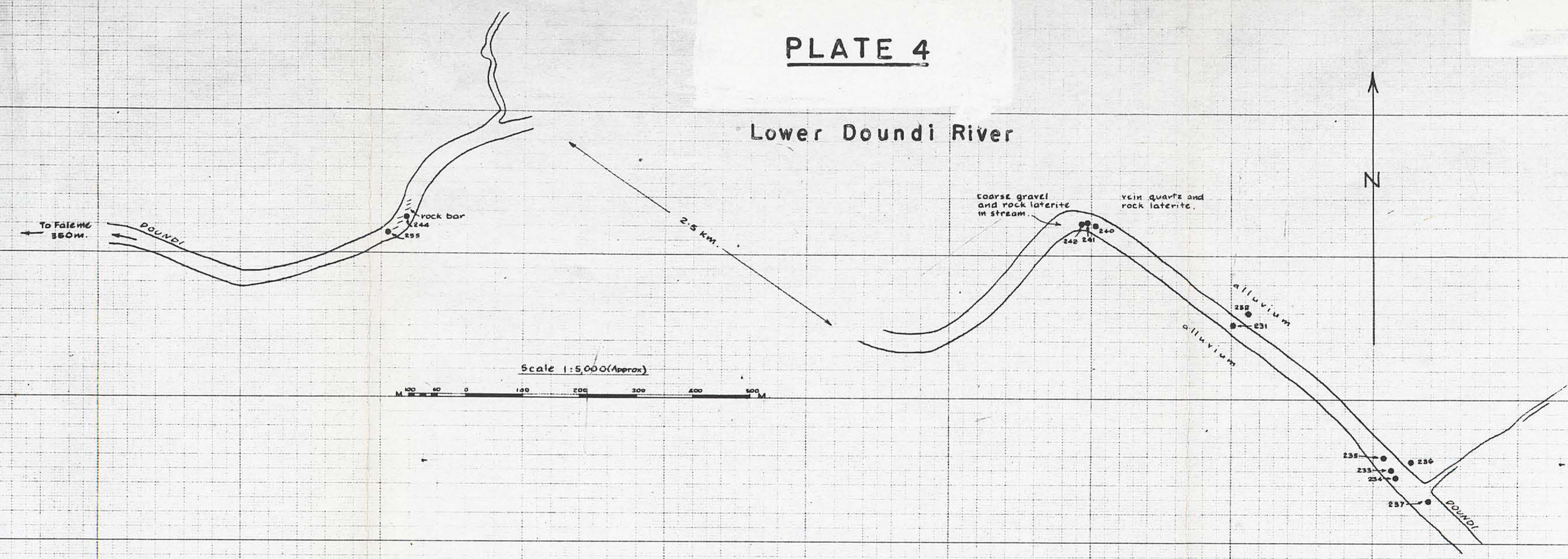


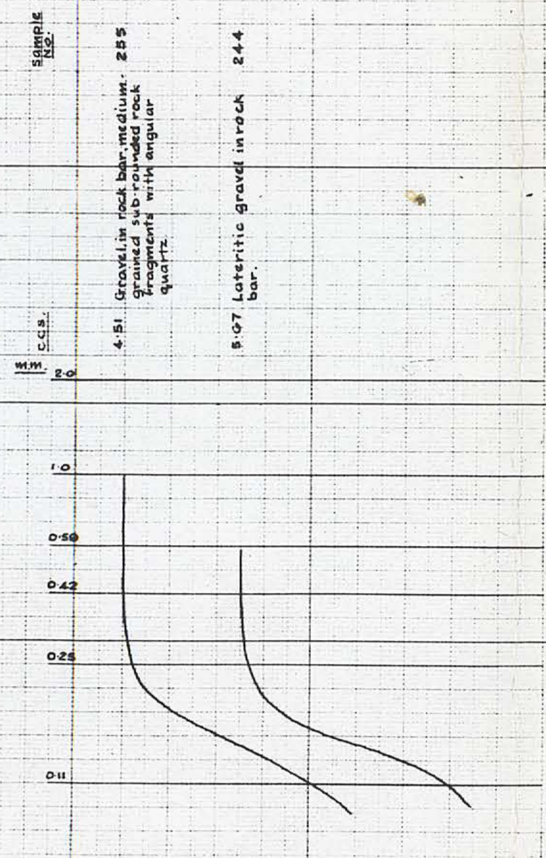


Cumulative Curves

PLATE 4

Lower Doundi River

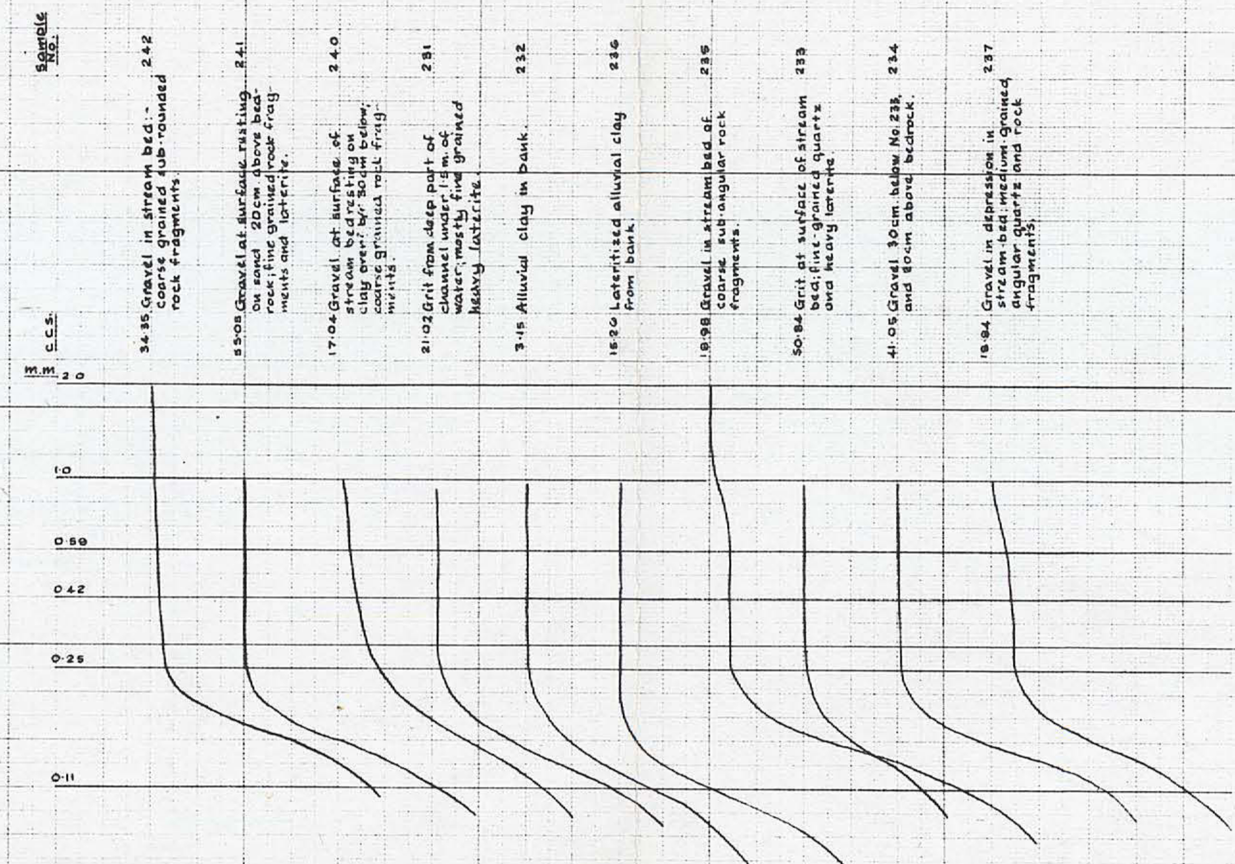




Cumulative Curves

DATA

Sample No.	<0·11	0·11	0·25	0·42	0·59	1	2	4
	m	i	l	l	i	m	e	t r e s
	c	c s.	o r	g	r	a	i n s	
255	0·64	3·25	0·18	Tr.	Tr.	4gr.	2gr.	-
244	0·52	4·90	0·25	Tr.	Tr.	-	-	-
242	2·1	29·7	1·42	0·09	0·55	0·5	8gr.	-
241	10·0	44·7	0·3	0·05	0·05	8gr.	-	-
240	2·08	13·0	1·45	0·5	0·81	0·1	-	-
231	5·25	15·6	0·27	0·07	0·1	4gr.	-	-
232	1·45	1·7	Tr.	Tr.	Tr.	2gr.	-	-
236	9·2	5·96	Tr.	Tr.	0·07	0·05	-	-
235	2·6	15·3	0·16	0·06	0·7	0·6	1gr.	-
233	18·6	3·19	0·34	Tr.	Tr.	1gr.	-	-
234	5·6	35·3	0·15	Tr.	Tr.	5gr.	-	-
237	3·63	13·2	0·35	0·36	0·12	0·1	-	-

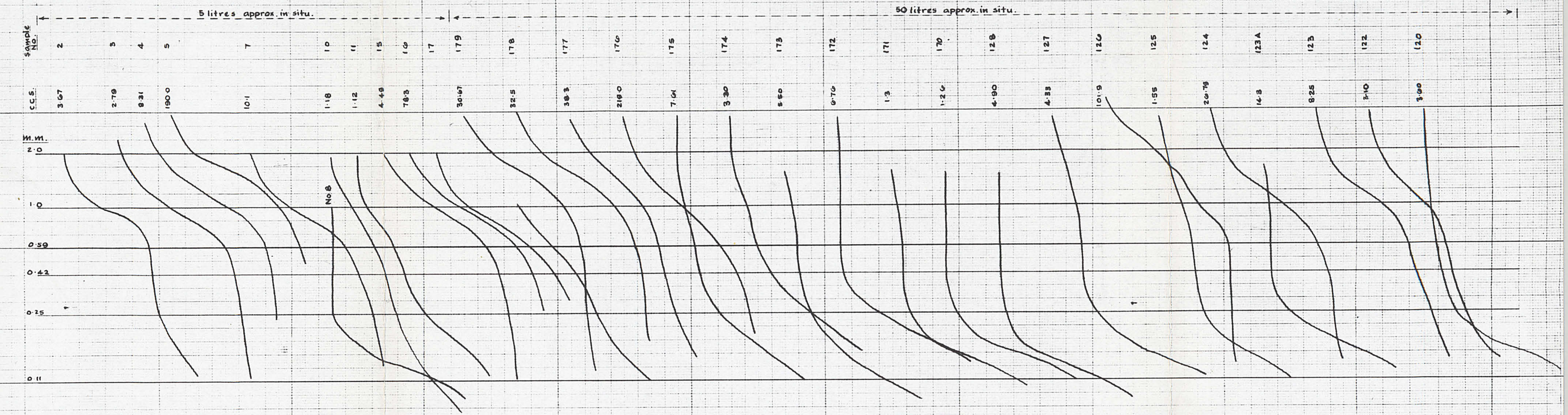


Cumulative Curves

PLATE 5

For location of samples see Plate 6

CUMULATIVE CURVES FOR SAMPLES ON STREAM DRAINING CIRQUE



CUMULATIVE CURVES FOR SAMPLES ON DIJIAMBA

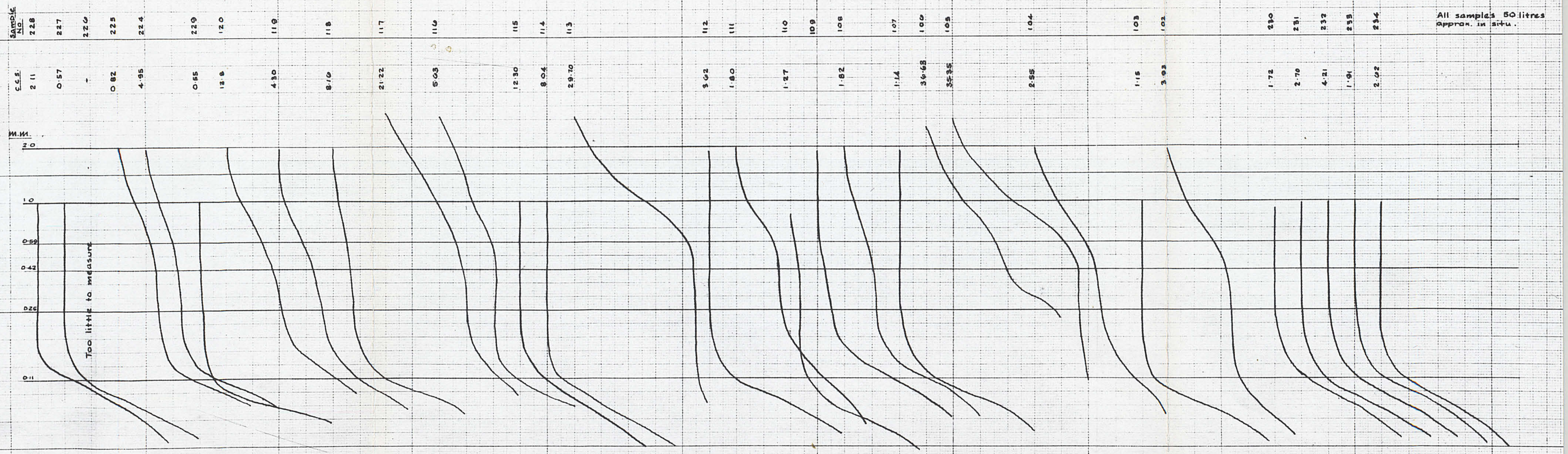


PLATE 6

PLAN SHOWING SAMPLE POSITIONS