EXPERIMENTAL APPROACH TO GRAIN-SIZE DATA INTERPRETATION

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ABSTRACT

Grain-size data of sediment samples are often plotted on log (phi)-probability paper with a view to identifying the lognormally distributed size populations. It is also customary to assign these lognormal grain-size populations to the different modes of transportation like rolling, saltation and suspension. The paper describes how this conventional approach was followed for interpretation of the transportational-depositional conditions of some Gondwana sediments, and also indicates how the clues obtained from controlled flume experiments might provide a more precise tool for interpretation of the flow velocity condition.

Flume studies show that water current has a preference for medium to fine sand grains which are lifted into suspension in much larger proportion than other grains, coarser or finer. The process leads to the generation of lognormal grain-size distribution in suspension loads, when flow velocities and heights of suspension above the bed are suitable.

Mixtures of lognormally distributed grain-size populations could be generated in suspension loads in flumes over a variety of sand beds at medium (60—110 cm/s) flow velocities. Nearly perfect lognormal grain-size distributions resulted when the flow velocity was increased. Mixtures of lognormally distributed grain-size populations therefore, need not necessarily represent different modes of transportation. On the otherhand, the degree of lognormality attained might prove to be an effective tool for deciphering the flow velocity condition under which a sediment population was transported and deposited in nature.

INTRODUCTION

Grain-size frequency distributions of sediments are believed to be environment sensitive, and sedimentologists have for a long time endeavoured to obtain clues to the environments of transportation and deposition from analysis of grain-sizes of sediment samples. Three different modes of approach are generally followed for interpretation of palaeo-environmental conditions from grain-size data. These are, in short: (1) comparison of grain-size distribution patterns of ancient sediments with those of modern sediments collected from known environments; (2) study of grain-size distribution patterns generated in laboratory flumes under simulated natural conditions; (3) theoretical interpretation of grain-size distribution patterns from the existing knowledge of hydrodynamics and sediment transportation.

The present state of knowledge of the forces operating in nature is so incomplete that a single line of approach often proves to be inadequate. An integrated approach combining the information drawn from the three different lines of study is likely to yield more complete information about palaeo-environment. Of the three above mentioned techniques moreover, the first and the third lines of approach often prove to be baffling; because the variables operating in nature are so many, and our knowledge of the dynamics of sediment transportation is so incomplete. Under such circumstances experimental

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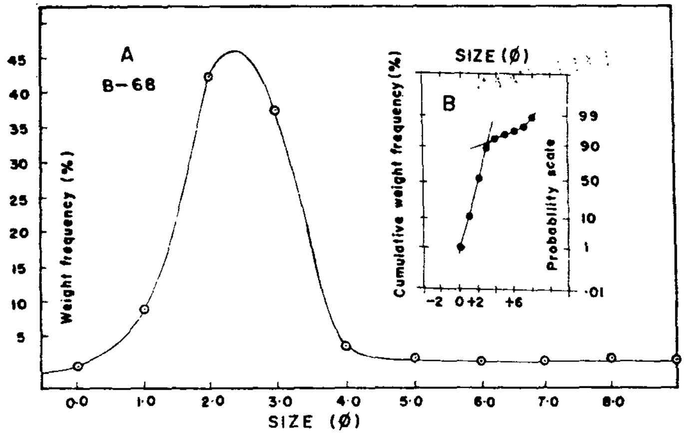

Figure 1 A. Grain-size frequency distribution of a Lower Kamthi sandstone sample from the Godavari valley.

Figure 1 B. Phi-probability plot of the cumulative grain-size frequency distribution of the Lower Kamthi sandstone sample shown in A.

studies in laboratory, under simulated, but controlled natural conditions might yield more dependable results. The present paper discusses this idea with specific reference to the procedures being followed for interpretation of the transportational conditions of some ancient fluviatile deposits.

The example used for the present discussion is from the Gondwana rocks of the Godavari valley, southeast India. Examination of primary sedimentary structures and sand body geometry of the Permo-Triassic Kamthi sandstones and siltstones belonging to the Gondwana in parts of the Godavari valley indicated that these were laid down by a system of ancient rivers (Sengupta 1970). A more detailed interpretation of the palaeo-environment was attempted through analysis of the grain-size frequency distribution patterns of these rocks.

CONVENTIONAL APPROACH : COMPARISON OF GRAIN-SIZE DISTRIBUTION CURVES

The method followed for palaeoenvironmental interpretation was essentially that of visual comparison of the Kamthi grain-size distribution patterns with those obtained by earlier workers from known depositional environments. Grain-size distribution patterns of the Gondwana sandstones closely followed the trend of "type-C" curve of Doeglas, which represents average river suspension deposit (Doeglas 1946). The Gondwana grain-size distribution patterns also compared well with the size distributions of sediments obtained from various present day river deposits (data of Fisk and others, compiled by Allen 1965).

Grain-size plots of the Gondwana samples on log (phi)-probability paper* showed several straight line segments indicating that each Gondwana sandstone sample was a mixture of several lognormally distributed grain-size populations (see Fig. 1 B). Of these, the coarser 95% generally consisted of a single lognormal population. The finer materials did not belong to a single

* Since statistical tests for normality of "weight frequency" data are not known it has been customary among the sedimentologists to depend on this approximate graphical test. If on a normal probability paper a straight line is a good fit to the plots of cumulative "weight frequency" percentages, against the sieve sizes in phi (ϕ) scale ($\phi = -\log_2$ diameter in mm, Krumbein, 1936), the size data are said to be lognormally distributed.

population at all, but were possibly incorporated into the main bulk of the sediment in several instalments. The conclusion reached from comparison of each segment of the grain-size distribution curve with the data available in the existing literature was that the medium to coarse grained sediments constituting the bulk of the Upper Kamthi represented the point bars of the Gondwana river. Presumably due to periodic turbulent currents comparatively finer grained materials were moved towards these point bars they settled from suspension during the waning phase of floods and infiltrated into the coarser sediments in several instalments (Sengupta 1970).

In conformity with this observation the CM plots (cf. Passega 1957) of the Kamthi sandstones indicated that the very coarse materials were transported by rolling, whereas the finer sand and silt were deposited as graded suspension or pelagic suspension. Although this interpretation gave a fairly consistent picture of the Kamthi sedimentation in the area, several basic questions still remained open. Why and under what condition should sand grains be transported as lognormally distributed size populations by rivers? What does this mean in terms of the hydrodynamic conditions of flow and the nature of the source material?

Log (phi)-probability plots of cumulative "weight frequencies" of sediment samples collected not only from fluvial deposits, but from a variety of other environments as well, often show up as mixtures of several linear segments. This suggests that each such sample is constituted of a number of distinct grain-size populations, each of which is lognormally distributed. Following Moss (1963) and Visher (1969) it has been customary among sedimentologists to interpret these linear segments as the grain-size populations transported as bed, suspension and saltation loads. The basic assumptions behind this approach are : (i) the grain-size populations transported as bed, suspension and saltation loads are distinguishable because they belong to distinct ranges of grain-sizes, and (ii) in each case the grain-size frequency distribution is lognormal. It is worthwhile to critically examine the validity of these assumptions before using the log (phi)-probability plots for environmental interpretation.

The conventional clear-cut division between the bed and the suspension loads have been questioned by some on the ground that all types of transition between the two exist. Near the bed the grains follow deterministic trajectories of jump whereas in suspension they follow random or probabilistic paths (Yalin 1972). Transitions between these two modes of transport are common in nature and it is not clear why the bed and the suspension loads should always show up as two distinctly different populations under such circumstances. The question is particularly true for the saltating grains which constantly change their positions between the bed and the suspension during transportation and are unlikely to be preserved in the deposit as a population distinct from the two.

The natural processes responsible for lognormal distribution of grain-size populations, the other crucial problem requiring close study in the context of the above discussion, has not been clear to the sedimentologists since it was first reported by Krumbein (1936). From

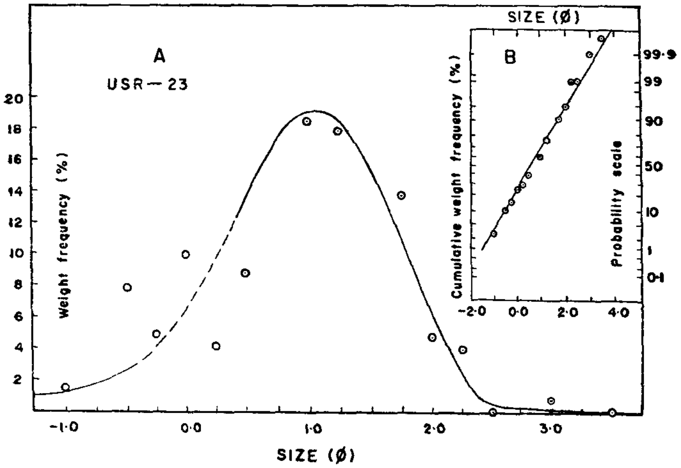

Figure 2 A. Grain-size frequency distribution of a sand sample collected from the Usri river point bar about 27 miles downstream from the source area.

Figure 2 B. Phi-probability plot of the cumulative grain-size frequency distribution of the sand sample shown in A.

time to time several theoretical models were proposed to explain this phenomenon (e.g. Kolmogorov 1941, Middleton 1970). However, critical studies have shown that it is difficult to find conditions in natural *fluvial* regimes which will fully satisfy the requirements of any of these theoretical models (Sengupta 1975c). The precise conditions for transportation of the ancient fluvial sands therefore, remained unclear and it was decided to trace the environmental condition in which lognormality of grain size distributions might be happening in nature today.

STUDIES ON RECENT FLUVIAL SEDIMENTS

With a view to finding the environmental conditions in which sand populations having lognormal grain-size distributions can accumulate in modern fluviatile regimes, a series of samples were collected from the point bars of the Usri river near Giridih, Bihar at various distances from the source. The grain-size distribution patterns of these samples were studied by sieving. Although the phi size distribution of the material in the source area of the river did not conform to the normal law, the sediments occurring on the river point bars at a considerable distance from the source, showed a definite trend towards linearity when plotted on log-probability paper (Fig. 2B). The sand samples which showed this trend occurred in thin, nearly horizontal, structureless laminae on top of the point bars. Apparently, the material was deposited either under high flow regime condition or was laid down from suspension during the waning phase of a flood.

Can a process of size sorting operating during transportation of sand either in suspension or as bed load (in high flow regime condition) generate lognormality of grain-size distribution? How can, in that case, the parameters of the grain-size frequency distribution of sand be correlated to the physical conditions of flow? These were the questions which followed naturally from this study. It is difficult to obtain answers to these questions from studies in natural river regimes where a number of unknown variables work simultaneously. In the next stage of work therefore, it was

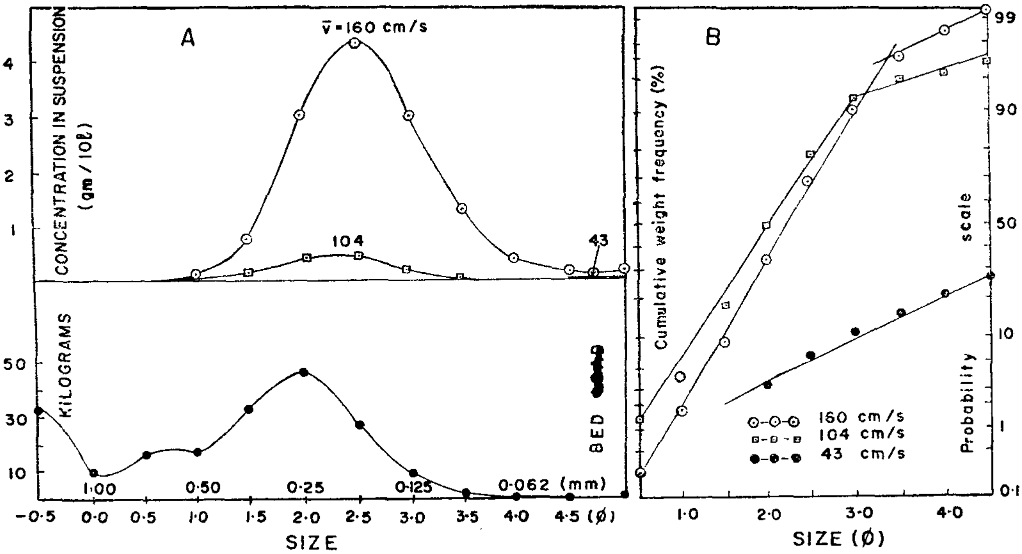

Figure 3 A. Grain-size frequency distribution of the suspended loads generated at different flow velocities in a laboratory flume over a sand bed having polymodal grain-size frequency distribution pattern. The bed load's grain-size distribution is shown in the lower diagram. $\bar{v}$ =mean flow velocity in cm/s.

Figure 3 B. Phi-probability plots of the cumulative grain-size frequency distributions of thesu spension load samples shown in A.

necessary to investigate into the process of size sorting in fluvial regimes through controlled experiments in laboratory flumes, where the influence of a single variable on the grain-size frequency distribution could be studied at a time.

EXPERIMENTAL APPROACH : FLUME STUDIES

Flume experiments carried out in the Groningen laboratory, Netherlands (Kuenen and Sengupta 1970) indicated that lognormal distribution of particle sizes can occur when sediments are *taken into suspension by high velocity* water flows. Field observations in the Usri river point bars together with these laboratory findings suggested that a process of size sorting operating during *suspension transportation might be res*ponsible for generation of lognormality of grain-size distributions in fluvial sand populations.

Following these clues, a series of flume studies were conducted in the Department of Physical Geography of the Uppsala University, Sweden. Grain-size frequency distribution of the materials taken into suspension by water at different flow velocities (and at different heights) from a bed of heterogeneous (polymodal) grain-size composition were studied in a large number of suspension load samples by sieving (Sengupta 1975 a,b). Fig. 3A shows the nature of the suspension loads at different velocities, at a height of 20 cm above this heterogeneous bed. Interestingly enough, grain-size distributions of the suspension loads were unimodal at

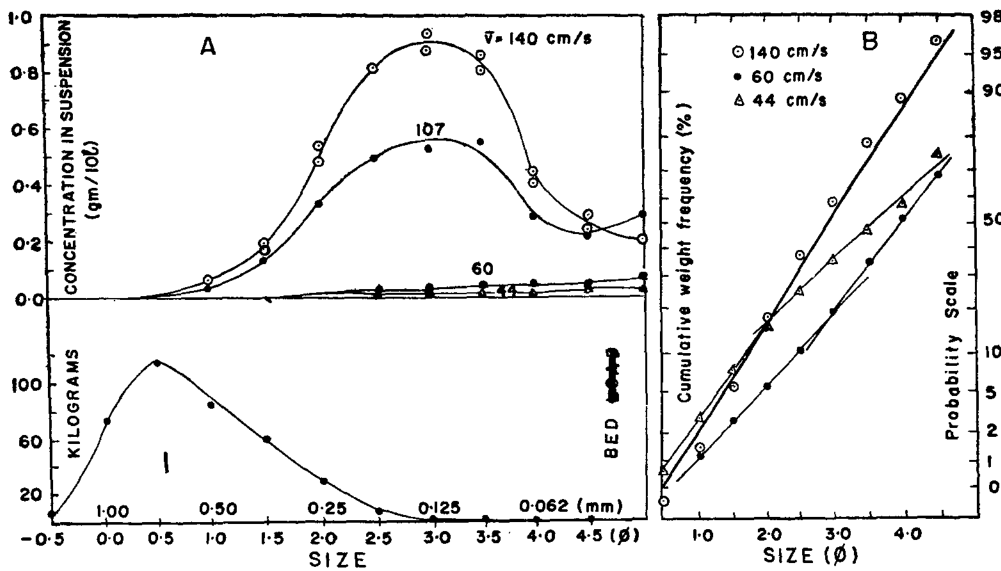

Figure 4 A. Grain-size frequency distributions of the suspended loads generated at different flow velocities in a laboratory flume over a sand bed having skew grain-size frequency distribution pattern. The bed load's grain-size distribution is shown in the lower diagram. $\bar{v}$ = mean flow velocity in cm/s.

Figure 4 B. Phi-probability plots of the cumulative grain-size frequency distribution of the suspension load samples shown in A.

all the three flow velocities. Moreover, with increase of flow velocity the size distribution became more and more symmetric around the mean size. Log-probability plots of the grain-size distributions of these suspension loads are shown in Fig. 3B. At the highest velocity (160 cm/s), grain-sizes of nearly 97% of the suspended particles are lognormally distributed, whereas at lower velocities only 92% (at 104 cm/s) and 26% (at 43 cm/s) of the total materials are lognormal. Two interesting clues emerge from these results : (i) the current has a definite tendency to take into suspension a unimodal grain-size population even when the bed's grain-size distribution is polymodal (ii) with increase of flow velocity there is a greater tendency for the grain-size distribution of the whole suspension load to attain lognormality. It is also clear that at lower velocities the load is constituted of a mixture of several lognormally distributed populations (Fig. 3B, v=104 cm/s.). Such mixtures therefore, need not necessarily represent the products of different modes of transportation. They might, on the other hand, be indicative of a particular flow velocity condition.

Since the first series of experiments conducted in 1971, these flume experiments have been repeated in the Uppsala flume laboratory with a variety of beds having different grain-size frequency distributions. Fig. 4 shows the result of one such experiment where the bed's grain-size distribution was highly skewed. The grain-size distribution of the suspension load above this bed however, was nearly symmetrical at

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SUMMARY AND CONCLUSIONS : Last line of paragraph-2 (p.101) should read as follows :

The mechanism of generation of lognormal grain-size distribution in water transported sediments is not fully understood. Particularly, it is not clear why the saltating grains which are transitory in nature between the bed and the suspension should be expected to be deposited as lognormally distributed populations having grain-size parameters distinguishable from both.

high flow velocities. Moreover, the modal size of the particles in suspension (3 ϕ or 0.125 mm) did not coincide with the mode of the bed load (0.5 ϕ or 0.71 mm). Similar results were obtained when the experiments were repeated with a variety of beds having different grain-size distribution patterns. These experiments indicate that the grain-size distribution pattern of the suspension load is nearly independent of the size-distribution pattern of the source material (the bed load). Irrespective of the nature of the bed load, the current always lifts into suspension an essentially unimodal grain-size population. Moreover, more of the intermediate size sand grains always go into suspension irrespective of the proportion in which they occur in the bed.

The earlier experiments have shown that the grain-size frequency distribution of the suspension load is dependent on (i) flow velocity (ii) height of suspension above the bed and (iii) grain-size distribution of the bed material (Sengupta 1975 a, b). While confirming these conclusions in a general way, the present series of experiments indicate that the grain-size frequency distribution of the suspension load hardly, if at all, reflects the actual grain-size distribution of the bed. By comparing the nature of the suspension loads at different flow velocities, it is also seen that with increasing flow velocity there is a tendency for the current to lift into suspension lognormally distributed grain-size populations. It is possible therefore, that the degree of lognormality of grain-size distribution attained, is a direct function of the flow velocity. Should it be possible to correlate the two, it would provide a new and useful tool for precise interpretation of the flow conditions under which sediment populations were transported and deposited in the geologic past.

SUMMARY AND CONCLUSIONS

The technique commonly followed for interpretation of transportational conditions of sediments involves visual comparison of the grain-size distribution pattern of the sediment sample with those obtained from known depositional environments of present day. The paper describes how this method was followed for interpretation of the depositional environment of the fluviatile Kamthi (Gondwana) rocks of the Godavari valley.

While giving broad clues to the palaeo-environmental conditions, the technique of visual comparison does not give precise information on the nature of the flow conditions responsible for transportation and deposition of the sediments. For more precise analysis it is customary to plot cumulative "weight frequency" percentages against logarithms of grain-sizes on probability paper in order to test whether the grain size distributions are lognormal. These plots often resolve into a number of straight line segments indicating that the sediment samples are mixtures of several populations, each of which is lognormally distributed. These populations are often attributed to the different modes of transportation like rolling, saltation and suspension. This technique of interpretation needs critical examination. The mechanism of generation of the suspension should be expected to be deposited as lognormally distributed populations having grain-size parameters distinguishable from both.

Field investigations of river transported sediments and controlled experiments conducted in laboratory flumes have shown that grain-size frequency distributions of sediment populations transported in suspension are generally lognormally distributed at high flow velocities. At medium (60-110 cm/s) velocities the cumulative frequencies of grain-sizes often show up as mixtures of several lognormally distributed populations. When the flow velocity was increased to about 150 cm/s, nearly 95% of the material in suspension exhibited almost perfect lognormal grain-size distribution. Mixtures of lognormally distributed grain-size populations therefore, need not necessarily be indicative of different modes of transportation. On the otherhand, the degree to which the grain-size frequency distribution approaches perfect lognormality, may be used as a measure of the flow velocity condition. This clue might lead to the formulation of a theoretical model correlating the parameters of grain-size distribution with that of the flow condition.

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I had an opportunity of discussing the experimental results with Professor S. Ray, only a few months before his death. Inspite of his ill health Professor Ray took keen interest in this work and gave some interesting suggestions. I recall this discussion with gratitude and I dedicate these pages to the memory of my teacher who introduced me to geological research.

REFERENCES

Allen, J. R. L., 1965 : A review of the origin and characteristics of recent alluvial sediments. Sedimentology, 5, 89-191.

Doeglas, D. J., 1946 : Interpretation of the results of mechanical analysis. J. Sedi. Petrol., 16, 19-40.

Kolmogorov, A. N., 1941 : Uber das logaritmisch normale Verteilungsgesetz der Dimensionen der Teilchen bei Zerstuckelung, Doklady Akad Nauk, CCCR, 31, No 2, 99 (in Russian and German).

Krumbein, W. C., 1936 : Application of logarithmic moments to size frequency distributions of sediments, J. Sedi. Petrol., 6, 35-47.

Kuenen, Ph. H. & Sengupta, S., 1970 : Experimental marine suspension currents, Competency and capacity, Geologie en Mijnbouw, 49 (2), 89-118.

Middleton, G. V., 1970 : Generation of the log-normal frequency distribution in sediments, in : Topics in Mathematical Geology (M.A. Romanova and O. V. Sarmanov, editors), 34-42, Consultants Bureau, New York.

Moss, A. J., 1963 : The physical nature of common sandy and pebbly deposits, part II, Amer. J. Sci., 261, 297-343.

Passega, R., 1957 : Texture and characteristic of clastic deposition, Amer. Assoc. Petrol. Geol. Bull., 41, 1952-1984.

Sengupta, S., 1970 : Gondwana sedimentation around Bheemaram (Bhimaram), Pranhita-Godavari valley, India, J. Sedi. Petrol., 40, 140-170.

Sengupta, S., 1975a : Size-sorting during suspension transportation—lognormality and other characteristics. Sedimentology, 22, 257-273.

Sengupta, S., 1975b : Sorting processes during transportation of suspended sediments—an experimental-theoretical study, UNGI Rapport, Naturgeografiska Institutionen, Uppsala University, 40, 49p.

Sengupta, S., 1975c : Experiments on lognormal size distribution of sedimentary particles, IX Intl. Sedim. Congress, Nice, Theme 6, Mecanique sedimentaire, 163-166.

Visher, G. S., 1969 : Grain-size distributions and depositional processes. J. Sedi. Petrol., 39, 1074-1106.

Yalin, M. S., 1972 : Mechanics of Sediment Transport, Pergamon Press, Oxford, 290p.