RECOGNITION OF FLUVIAL ENVIRONMENTS IN THE BIYADH-WASIA SANDSTONES (LOWER-MIDDLE CRETACEOUS) AS REVEALED BY TEXTURAL ANALYSIS[1]

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ABSTRACT: A detailed study of the Biyadh (upper Lower Cretaceous) and Wasia (Middle Cretaceous) Sandstones in central Saudi Arabia was undertaken to describe their sedimentologic texture and to use some of the available techniques of environmental analysis in determining their depositional environments. Bivariant plots and frequency distribution curves indicate that fluvial deposits dominate over either beach or dune deposits in the Biyadh and Wasia Sandstones.

INTRODUCTION

Mason and Folk (1958) and Friedman (1961), in detailed investigations of modern sands, have shown that dune sand are generally positively skewed, while beach sands are negatively skewed. Furthermore, Mason and Folk (1958) have indicated that dune sands are generally better sorted than beach sands, while Friedman (1961) pointed out that dune sands tend to be better sorted than river sands. Additionally, Moiola and Weiser (1968) concluded that several combinations of textural parameters are environmentally sensitive and very effective in differentiating between beach, river, and dune sands. They also added that parameters calculated from quarter-phi sieve data, as in the present study, are the most sensitive. In most cases half or whole phi parameters are almost as effective in differentiating environments.

The purpose of this contribution, therefore, is to describe the Biyadh and Wasia grain-size textures based on bivariant parameter combinations and to determine their depositional environments.

Because of similarity in lithology and sedimentary features, the Biyadh and Wasia sandstones are considered as a single sedimentary unit. Different units within the Biyadh-Wasia are indicated in some illustrations for comparison purposes.

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PROCEDURES

About 200 size analysis curves of selected sand samples collected from eight outcrop sections, x-x′ traverse-section, and from borehole PW_3 have been plotted (see Fig. 1). Folk's (1968) statistical parameters of grain size have been applied here. Initially the size-distribution curves (i.e., cumulative curves) of these selected sand samples were constructed on arithmetic probability paper using the phi scale.

In the present study the graphic textural parameters, i.e., mean (Mz), standard deviation (σ_1), skewness (SK_1), and kurtosis (KG) have been calculated from the cumulative curves, using the formulae devised by Folk and Ward (1957).

GENERAL SETTING AND STRATIGRAPHY

Within the area (Fig. 1) the distribution of both the Biyadh and Wasia Sandstones can be traced almost continuously from Wadi as Sahba north to Wadi al Atk, a distance of nearly 250 km. The Biyadh (upper Lower Cretaceous) Sandstone ranges in thickness from 360 to 625 meters in central Arabia (Powers et al., 1966). Moshrif (1976) has estimated that within the area studied the thickness of the Biyadh Sandstone ranges from 300 to 400 meters (based on $x - x'$ and $y - y'$ traverse-sections, the borehole PW_3, and other studied sections; see Fig. 1). Powers et al. (1966) indicated that in central Arabia the thickness of the overlying Wasia (Middle Cretaceous) Sandstone in-

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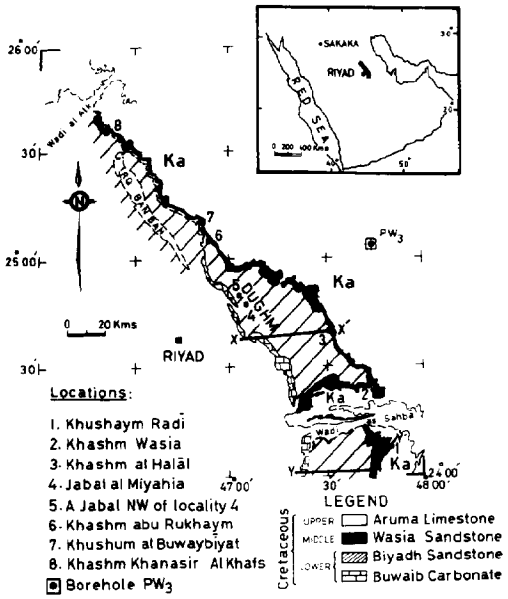

FIG. 1.—Locality map showing general distribution of Cretaceous rocks in central Saudi Arabia. Inset (upper right) indicates location of study in the Arabian Peninsula.

creases irregularly but persistently from south to north. They estimated a 40 m thickness at Wadi as Sahba, 60 m near Khashm Khafs (near Wadi al Atk) and a maximum thickness of 285 m near Sakaka (in northwestern Arabia). Within the area concerned, Moshrif (1976) has shown that the thickness of the Wasia varies between 12–20 m in outcrop sections and is nearly 185 m thick in borehole PW_3 to the east.

Although the Wasia is a much more ferruginous sandstone than the Biyadh, both sequences show very little variation in lithological composition and contain no fauna throughout. The sandstone beds generally display varied colours of purple, red, pale, pink, grey to light yellow, and white to dull white. Both sequences include graded beds and are friable and poorly cemented. Some beds contain carbonaceous wood fragments, and nearly all the beds are badly weathered. A few conglomerate units were recognised at the base of several observed fining-upward cycles within both formations (Moshrif, 1976).

Most of the Biyadh and Wasia sandstone units show structures such as cross-stratification (planar), cross-lamination, horizontal lamination, parallel lamination, deformed cross-stratification, and a few symmetrical ripples and some biogenic disturbances (Moshrif, 1976).

The conformable contact of the Biyadh with the underlying Buwaib Formation is marked by a conspicuous change in the character of the residual gravels on the surface, reflecting the major change in lithology from the friable dark brown ferruginous Biyadh sandstones to the creamy to tan-white carbonate of the underlying Buwaib (Moshrif, 1976). A more distinct and well-established disconformity between the Wasia Sandstone Formation and the overlying Aruma (Upper Cretaceous) Limestone Formation is recognised on the basis of the marked lithological and faunal contrasts between these two rock units.

GRAIN-SIZE DISTRIBUTION

Many workers have contributed towards the interpretation of grain size distributions. Visher (1969) in his work on the size distributions of modern sands and the relationship of these to ancient sands and their depositional processes has shown that most distributions comprise one or more sub-populations, each of which displays a log-normal distribution. These sub-populations reflect three modes of sediment transport, i.e., saltation, suspension, and traction. The number, amount, size range, and mixing of the populations vary in relation to provenance, sedimentary process, and sedimentary dynamics. A number of processes may be uniquely defined in log probability curves, and on this basis, Visher (1969) has assigned specific curve shapes to the sands formed in various recent environments, i.e., eolian dune, fluvial, deltaic, tidal channel, wave and turbidity current. This approach, if valid, provides a genetic and fundamental basis for interpreting grain size distributions, and therefore the grain-size curves of the sands sampled in the present study have been interpreted according to Visher's (1969) results. See Figure 2.

Figure 2 displays cumulative curves selected as representative of the main types of grain-size distribution encountered in the present study. This figure shows that salta-

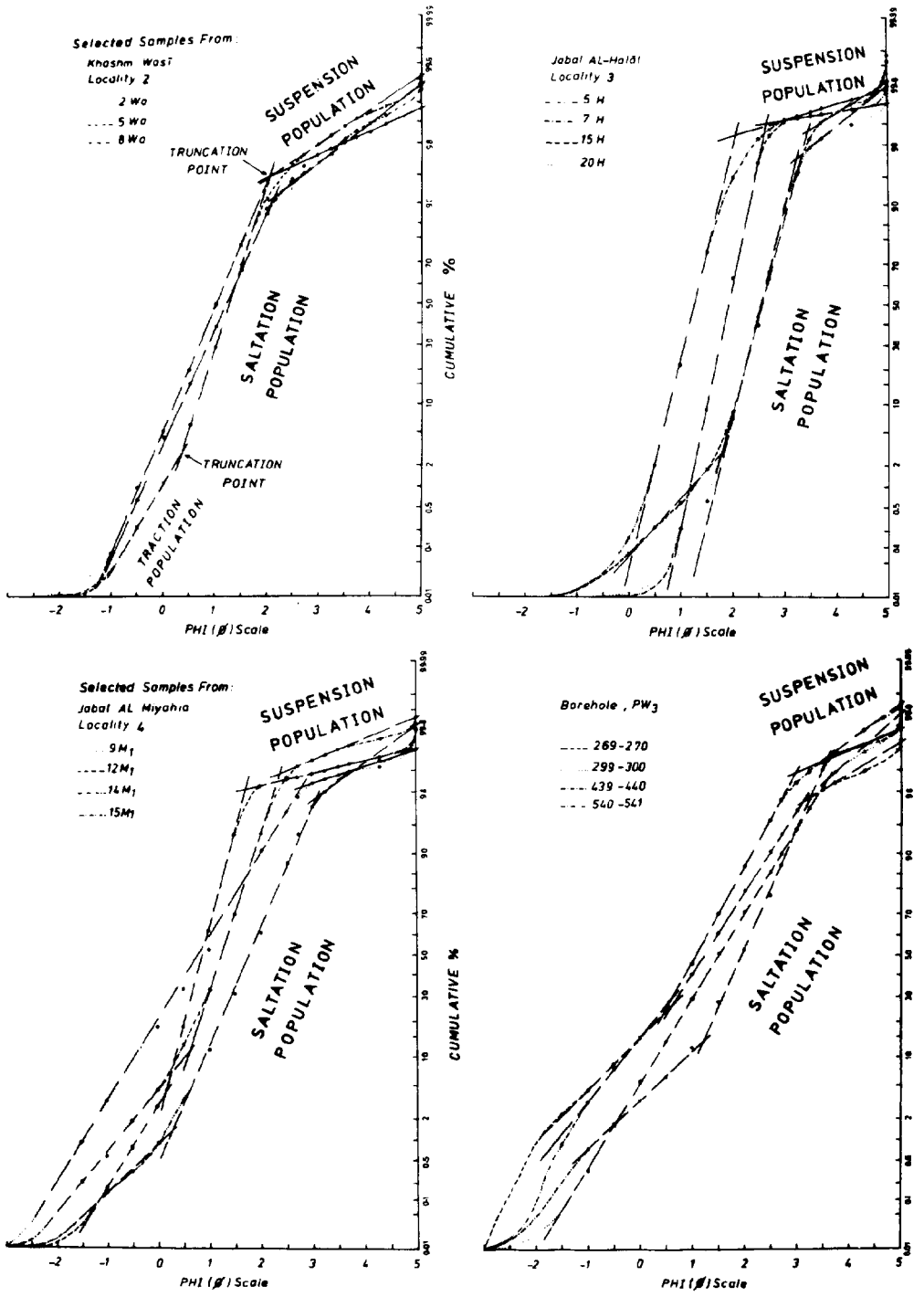

FIG. 2.—Representative grain-size distribution curves from the Biyadh/Wadia Sandstones. Samples are plotted showing the populations suggested by Visher 1969.

tion and suspension dominate the size-populations or distributions, although a few curves reflect the presence of a population belonging to the third traction mode. The saltation population comprises between 90 to 95 percent of the total grain size distribution. The truncation points between the suspension and the saltation populations are variable but generally occur between 1.5 to 3.5 Phi. The suspension population comprises 1 to 5 percent of the distribution. A few samples contain a very small percentage of the third mode, the traction population, which rarely exceeds 2 percent of the entire distribution. The trucation point between the saltation population and the coarser traction population generally occurs somewhere between 0.5 and 1.5 Phi, (see Fig. 2). The size range (from 0.5 to 3.0 Phi) in the saltation population strongly suggests a slope or sorting intermediate between deposits formed by suspension and those produced by waves or oscillatory currents.

The presence of the suspension population and the truncation of the coarse population (saltation) could be interpreted as indicative of a positive skewness resulting from deposition in dunes. Moreover, the significance of the saltation population in wind transport of sediment and its predominant presence in the sample studied (Fig. 2) may suggest a genetic relationship. Furthermore, the lack of competence of eolian processes to move a coarse population by surface creep or rolling along the surface (Bagnold, 1953) is indicated here by the almost complete absence of the traction population (Fig. 2). The presence of 1 to 5 percent of the suspension population may indicate the operation of unidirectional fluvial transport.

The size distributions for the Biyadh and Wasia samples, represented by Figure 2 show some fundamental similarities to those described by Visher (1969) in his Figure 11D, 15, and 16 and which have been classified respectively as Mississippi River Delta environment (distributary channel), modern fluvial channel sands, and ancient fluvial sandstones. Nearly all localities sampled yield typical fluvial-type size-distribution (as defined by Visher, 1969, 1972), which are typified by the representative cumulative curves which show only two main size populations (i.e., saltation and suspension) (e.g., curves for samples 2Wa, 8Wa, 5H, 7H and 20H, in Fig. 2), which are characteristic of fluvial processes and most resemble curves derived from sand in upper deltaic environments.

Moreover, the third size element, i.e., population ascribed to traction or surface creep, when present is normally coarser than 1.0 ϕ (0.5 mm). Visher (1969) has indicated a similar distribution. He related the occasional presence of this third element in fluvial deposits as "strongly provenance controlled and is developed most frequently in the deepest portion of the channel." The between-sample variation in the proportions of sediment, each size-population also may be attributed to variations in flow velocity and is very probably controlled by sediment reworking.

The selected curves (Fig. 2) may possibly reflect wind influence perhaps in the form of dunes adjacent to fluvial channels in an arid environment, or more probably the sands are derived from the exposed upper surface of fluvial point-bars (Moshrif, 1976) which have been partially reworked by the prevailing wind. These curves therefore allow significant modification of the environmental interpretation of the Biyadh/Wasia Sandstones and, furthermore, largely confirm the conclusions of Visher (1969).

BIVARIANT GRAIN-SIZE PARAMETERS

Friedman (1961 and 1967) has used scatter plots of moment parameters to differentiate between river and beach sands. Figures 15 and 16 in Friedman (1967) are based on the graphic distribution of Folk and Ward (1957). Friedman's Figure 15 (1967) represents a plot of inclusive graphic skewness versus inclusive standard deviation, which permits a good separation between beach and river sands. Whilst his Figure 16 is a plot of inclusive graphic skewness versus graphic kurtosis which shows no major differentiation between the two environments. Similarly Moiola and Weiser (1968) showed many scatter plots to differentiate between modern beach, dune (inland and coastal), and river sands. Moiola and Weiser's Figures 6A and 8C (1968) reflect a combination of mean diameter versus standard deviation and are considered to be most effective in differen-

tiating between river and beach sands, coastal dune, and river sands respectively. Since differences between the graphic parameters are relatively small (Folk and Ward, 1957), the "environmental boundaries" of Friedman (1961, 1967) and that of Moiola and Weiser (1968) are perhaps the best tool to use in differentiating between the environments represented in the Biyadh and Wasia Sandstones. The boundaries of Friedman (1961), Friedman (1967), and Moiola and Weiser (1968) are shown on the relevant figures of this report.

The Biyadh-Wasia data are plotted in the following forms: mean size versus standard deviation (Figs. 3, 4), skewness versus standard deviation (Figs. 5, 6), skewness versus mean size (Figs. 7, 8). Cumulative curves are presented in Figures 2 and 9. Table 1 summarizes the interpretation of the Biyadh-Wasia Sandstones derived from the bivariant plots. It shows percent estimates of contributions of fluvial, dune, and beach sands in outcrop, borehole PW_3, and traverse x-x samples.

Folk and Ward (1957) indicated that the graphic parameters provide good approximations of the moment parameters. This was tested on a few of the Biyadh and Wasia samples and the difference between these two parameters appeared negligible. However, Friedman's (1961, 1967) discriminating boundaries, which are based on moment summation calculation, can be applied to the present graphic bivariant figures.

Friedman (1961) and Moiola and Weiser (1968) have considered that plotting mean size versus standard deviation provides an effective discrimination between river, dune, and beach sands. Friedman's (1961, Fig. 5) environmental boundary line, based on moment summation calculations, is reproduced here (Figs. 3, 4) and is applied to the graphic parameters of the Biyadh-Wasia Sandstones. Moiola and Weiser (1968, Fig. 5A) indicated that the same boundary clearly separates the graphic data of modern river and inland dune sands.

Using the reproduced discriminate fields of Friedman (1961, Fig. 5; i.e., dune, river, and mixed dune or river fields), we observe that about eighty percent of the Biyadh and Wasia outcrop samples (Fig. 3; Table 1) plot in the mixed dunes or river field, twenty percent in dune, and two percent plot in river fields. Comparably, all the borehole PW_3 samples (Fig. 4; Table 1) are in the mixed dune or river field, while the traverse x-x′ samples (Fig. 4; Table 1) are distributed as follows: fifty six percent in the dune field; six percent in the river field; thirty five percent in the dune or river field; and three percent left undetermined. Again if we just consider the reproduced boundary line of Friedman (1967, Fig. 14, i.e., between beach and river), we find that in Fig. 3 (see also Table 1), sixty percent of the Biyadh-Wasia outcrop samples are distributed in the beach field and the remaining forty percent appear in river field. But Figure 4 and Table 1 show that ninety eight percent of the borehole samples are plotted in river field and only two percent plot in the beach field. Seventy eight percent of the traverse x-x′ samples are labelled beach; sixteen percent river; and six percent left undecided by Friedman's (1967, Fig. 14) diagram (see Table 1). However, when applying the boundary lines of Moiola and Weiser (1968, Figs. 6A, 8C), Figures 3 and 4 show that ninety or more percent of the Biyadh-Wasia samples (i.e., from the outcrop, the borehole, and the traverse sections) are distributed in the river field (See Table 1).

This discrepancy of interpretation deduced by the bivariant analyses for the Biyadh-Wasia Sandstones (Figs. 3, 4, Table 1) using the above discriminate fields of Friedman (1961, Fig. 5; 1967, Fig. 14) and Moiola and Weiser (1968, Figs. 6A, 8C), are perhaps due to the consideration of the applied discriminatory techniques where the examined samples are assumed to be composed of either dune, beach, or river sands. It is also probable that the limited number of environments considered, and the applied techniques have ignored the effects of regional variation in grain size, climate, sedimentation rate, and relative energy conditions within the final environment (Amaral and Pryor, 1977). Moreover, such a large difference between the two interpretations in the present bivariant applications (i.e., Friedman, 1961, 1967; Moiola and Weiser, 1968) is perhaps that these field boundaries are totally subjective and empirical lines, and thus the two investigators applying the same combination of parameters may delineate entirely dif-

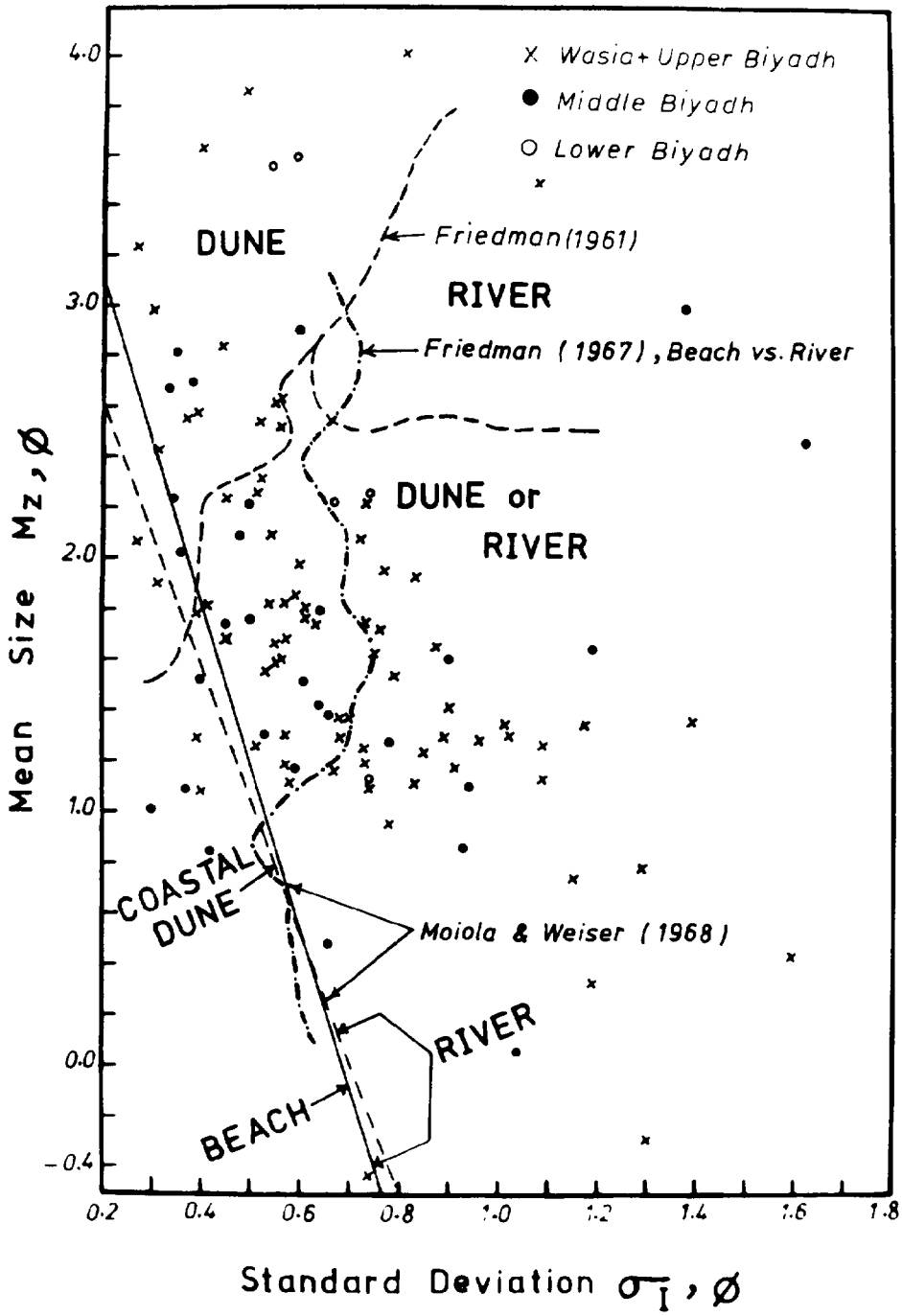

FIG. 3.—Bivariant plot of mean size versus inclusive standard deviation, using Friedman's (1961, 1967) and Moiola and Weiser's (1968) boundary lines. Samples selected from the Biyadh/Wasia outcrop sections.

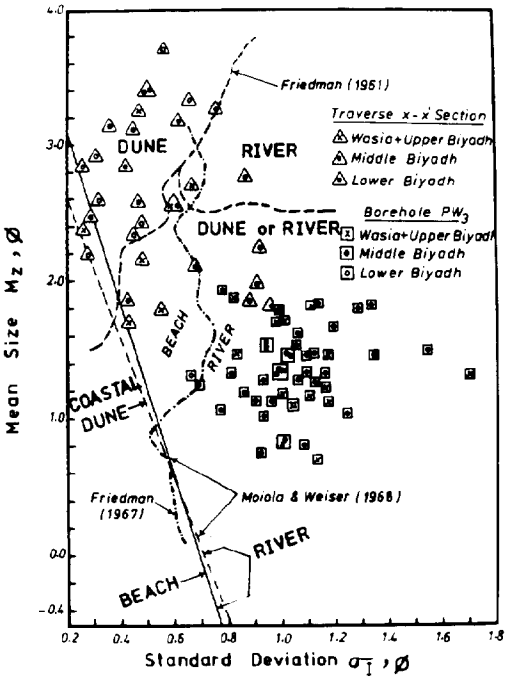

FIG. 4.—Bivariant plot of mean size versus inclusive standard deviation, using Friedman's (1961, 1967) and Moiola and Weiser's (1968) boundary lines. Samples selected from the Biyadh/Wasia traverse section and borehole PW_3.

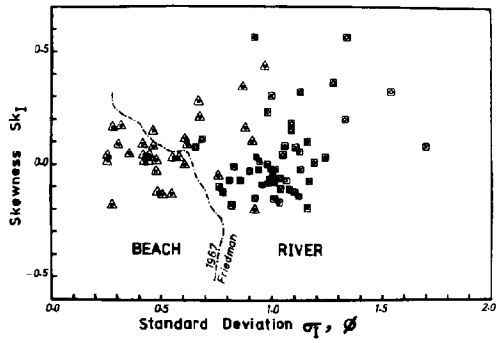

FIG. 6.—Bivariant plot of skewness versus inclusive standard deviation. Samples selected from the Biyadh/Wasia traverse section and borehole PW_3 (symbols as in Fig. 4).

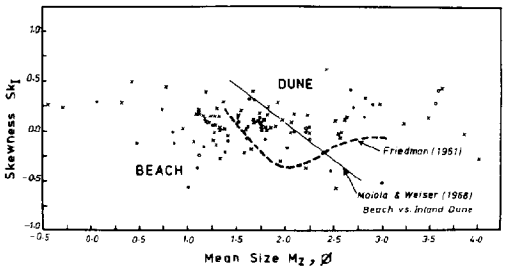

FIG. 7.—Bivariant plot of skewness versus mean size. Samples selected from the Biyadh/Wasia outcrop sections (symbols as in Fig. 3).

ferent discriminatory fields for a specified set of environments (Amaral and Pryor, 1977).

Friedman's (1967, Fig. 15) discriminatory field of environments (i.e., beach and river) using inclusive graphic skewness versus inclusive graphic standard deviation (sorting) values is reproduced in Figures 5 and 6 using the inclusive graphic size parameters of the Biyadh-Wasia data. The tested outcrop and borehole samples appear more in the river rather than in the beach field, while those samples of the traverse section appear more in beach field (see Figs. 5, 6, Table 1).

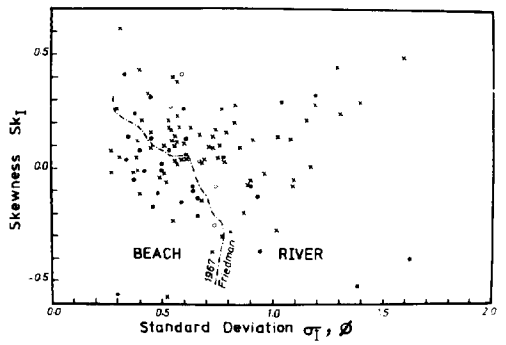

FIG. 5.—Bivariant Plot of skewness versus inclusive standard deviation. Samples selected from the Biyadh/Wasia outcrop sections (symbols as in Fig. 3).

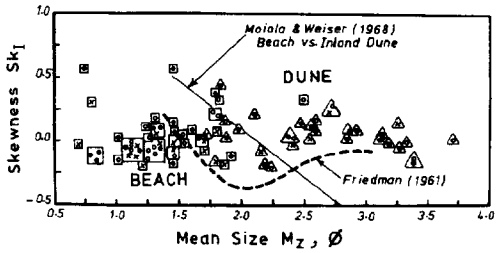

FIG. 8.—Bivariant plot of skewness versus mean size. Samples selected from the Biyadh/Wasia traverse section and borehole PW_3 (symbols as in Fig. 4).

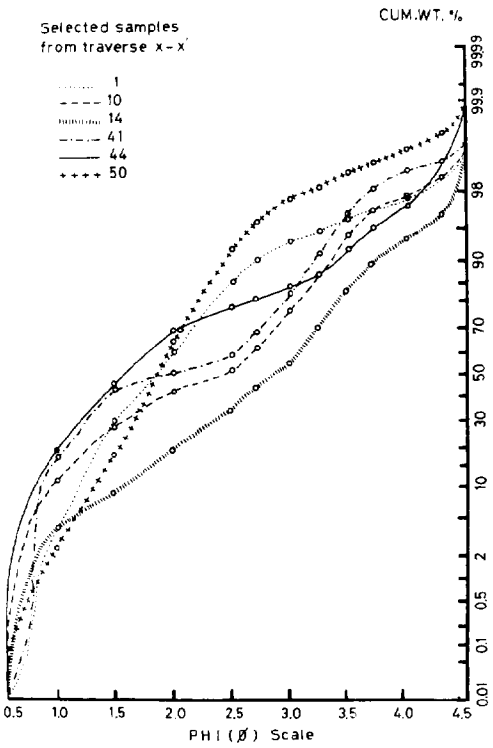

FIG. 9.—Cumulative curves of samples selected from the traverse x-x′ in the Biyadh Sandstone. Note bimodality in samples 10, 41, and 44.

Plots of skewness versus mean size have been proposed to be the most effective discriminator between beach and dune sands (Friedman, 1961; Moiola and Weiser, 1968). Although both Friedman (1962) and Folk (1966) indicated that the method of moments measures is a slightly different property than the graphic method, Hails (1967) showed in his Figures 3 and 4 (i.e., based on moment and graphic method respectively) that the difference between the two methods is negligible. Because Friedman's (1961) moment-measured discriminatory fields, i.e., beach-dune boundary, may not always be consistant with the graphic parameters method of Folk (1966), the graphic grain-size parameters of the Biyadh-Wasia data were plotted on a diagram based on graphic measures (Hails, 1967, Fig. 4) which is compatible with and resembles Friedman's (1961) Figure 1. Figures 7 and 8 plotting inclusive graphic skewness versus mean size are used for differentiating between beach and dune sands. The environmental fields of Friedman (1961, Fig. 1) and those of Moiola and Weiser (1968, Fig. 3C), which are reproduced in Figure 7 and 8, show variable percentages of plots in beach and dune environments for the concerned sandstones (Table 1). Table 1 summarizes percent estimates of the predicted environmental contributions of fluvial, and beach and dune sands as revealed by the bivariate grain-size parameter techniques applied to all samples from the Biyadh-Wasia Sandstones.

Although all the cumulative curves of the Biyadh-Wasia samples have shown unimodal distribution as appeared in the earlier grain-size distribution section (Fig. 2), a few cumulative curves of some samples from the x-x′ traverse show slight bimodality (Fig. 9), and these are worth noting. This is perhaps indicative of a dual source of sand supply which may have been the original fluvial source in addition to; (i) a dune supply obtained by wind reworking part of the exposed fluvial sands, (ii) or, since most Biyadh sands are friable, it is possible that sands from higher levels of the Biyadh in the area have been introduced by present winds, seasonal rainfall, or ephermeral

TABLE 1.—*Proportionate distribution of predicted Biyadh/Wasia paleonvironments inferred from different combinations of grain-size parameters and assigned to the environmental "fields" of Friedman (1961, 1967) and Moiola and Weiser (1968). (Note: All percentages in this table are based on summation of all samples from the Biyadh-Wasia Formations)*

Selected Samples From	Friedman (1961) Mean size vs. St. Dev. (M_z) (σ_T)			Friedman (1967) Mean size vs. St. Dev. (M_z) (σ_T)		Moiola & Weiser (1968) Mean size vs. St. Dev. (M_z) (σ_T)		Moiola & Weiser (1968) Mean size vs. St. Dev. (M_z) (σ_T)		Friedman (1967) Skewness vs. St. Dev (Sk_I) (σ_T)		Friedman (1961) Skewness vs. Mean Size (Sk_I) (M_z)		Moiola & Weiser (1968) Skewness vs. Mean Size (Sk_I) (M_z)	
Outcrop Measured Sections n=111	Dune 20	River 2	Dune or River 78	Beach 60	River 40	Coastal Dune 8	River 92	Beach 10	River 90	Beach 33	River 67	Beach 36	Dune 49(15-UD)*	Beach 69	Inland Dune 28
Borehole PW_3 n=51	0	0	100	2	98	0	100	0	100	0	100	71	25(4-UD)*	92	8
Traverse x-x′ n=32	56	6	35(3-UD)*	78	16(6-UD)*	0	100	9	91	66	34	0	72(28-UD)*	25	75

n = No. of Samples analysed. *UD = Undetermined

steams into the porous sandstones sampled at ground level in the x-x′ traverse; (iii) or, more probably, the x-x′ surface traverse samples have been contaminated by recent non-Biyadh wind blow sands as most of the traverse x-x′ beds are mantled temporarily by recent sands and gravels. To confirm such contamination, it would be necessary to test these samples against modern sand dune samples from this area.

Nearly all authors have noted that plots of skewness versus kurtosis provide the least environmental indicators. When it was tested on the Biyadh-Wasia samples using their inclusive graphic skewness versus graphic kurtosis, the obtained result is similar to that reached by Friedman (1967, Fig. 16), where a maximum overlap appeared and a less satisfactory separation of environmental fields was possible. Additionally, such unpresented plots (i.e., skewness vs kurtosis) of the Biyadh-Wasia Sandstones have shown no discernible environmental significance, except that the majority of the plotted points tend to cluster together in a semicircular field, resembling the cluster designated by Folk and Ward (1957, Fig. 17) as field G, with the central point of the field displaced away from the intersection of the two normal curves in the direction of more positive skewness. This field represents the nearly pure sands, with less than 1 percent gravel and less than 5 percent silt (Folk and Ward, 1957). On the other hand, when Moiola and Weiser's (1968, Fig. 3E) boundary line is applied to the same plots, it shows that the majority of samples are labelled beach rather than inland dune environment. This discrepancy is interpreted as due to the poor environmental sensitivity of both skewness and kurtosis, particularly when plotted against each other.

Similarly, plots of kurtosis versus mean size provide the least information about environmental differentiation. Sample points seem to be scattered randomly across each diagram, except that the traverse x-x′ samples tend to form a separate field from those obtained from the borehole, PW_3, and scatter in the finer direction, (i.e., toward 4.0 ϕ or 1/16 mm). This again may suggest that more silt and clay fractions were added to the original coarser sands by winds and/or ephemeral streams. It could also be that the finer portion of sediments were carried down through the present x-x′ superficial beds.

DISCUSSION AND CONCLUSION

Environmental interpretations of the Biyadh-Wasia Sandstone Formations as a single unit have been approached based on their grain-size distribution curves and the bivariant grain-size parameter combinations. The various interpreted sedimentary environments suggested by the bivariant figures for the Biyadh-Wasia sands are summarized in Table 1.

This table and the bivariant plots indicate that river (fluvial) deposits dominate both beach and dune deposits in the Biyadh-Wasia Sandstones. This is to be anticipated where dune sands develop adjacent to fluvial channel sands in an arid region with a mix of the two environments. It is probable that sands derived from the exposed upper surfaces of the fluvial point-bars of the Biyadh-Wasia may have been partially reworked by the prevailing winds in the area and were introduced into the main fluvial channel sands (Moshrif, 1976). Furthermore, most localities sampled yield typical fluvial-type size-distribution which are typified by the representative cumulative curves showing saltation and suspension. These are characteristic of fluvial processes and most resemble curves derived from sand in upper deltaic environments.

The environmental interpretations, based on the application of the bivariant plots of grain-size parameter combinations for the Biyadh-Wasia Sandstones, have perhaps shown inadequate and less satisfactory results. This is most probably due to the extreme subjectivity of the method together with oversimplification of the involved discriminating boundaries and may produce unreliable results for anticipating ancient depositional environments. However, the use of such methods are still useful and suggestive enough to assign a certain and a predominant environment for a certain ancient deposit (Table 1). However, this worker is convinced that a much better approach toward a satisfying and a reliable prediction of ancient Biyadh-Wasia sedimentary environments is clearly made through the application of grain-size distribution curve

techniques of Visher (1969). These techniques have certainly confirmed and supported the recognition of fluvial environments in the Biyadh-Wasia Sandstones in central Arabia.

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