William F. Tanner
on
Environmental Clastic Granulometry

Florida Geological Survey
Special Publication No. 40

Compiled by:
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State of Florida
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Florida Geological Survey
Walter Schmidt, *State Geologist and Chief*

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Florida Geological Survey
Tallahassee, Florida
1995

LETTER OF TRANSMITTAL

Florida Geological Survey
Tallahassee

Governor Lawton Chiles
Florida Department of Environmental Protection
Tallahassee, Florida 32301

Dear Governor Chiles:

The Florida Geological Survey, Division of Administrative and Technical Services, Department of Environmental Protection, is publishing "William F. Tanner on Environmental Clastic Granulometry" as its Special Publication 40. This document shall be of use to the State as a source of information related to sampling, analysis, and interpretation of the significantly large volumes of sedimentary lithologies of Florida. Such work is a necessity and is important to consider when addressing environmental concerns and issues on the behalf of the welfare of the State of Florida.

Respectfully yours,

Walter Schmidt

Walter Schmidt, Ph.D., P.G.
State Geologist and Chief
Florida Geological Survey

KEY WORDS:
Beach, Depositional Environments, Eolian, Grain Size, Granulometry, Fluvial, Kurtosis, Lacustrine, Littoral, Moment Measures, Probability Distribution, Settling, Sieving, Skewness, Suite Statistics, Wave Energy.

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FOREWORD

Among his many other geological pursuits, Dr. William F. Tanner has over 45 years of experience in sedimentologic studies and applications. He was chairman for the 1963 Society of Economic Paleontologists and Mineralogists (S. E. P. M.) interdisciplinary ***Inter-Society Grain Size Study Committee*** which established sedimentologic standards that remain the basis for sedimentologic work. His combined experience and expertise is of a calibre not commonly found at universities, let alone available for other instructional opportunites.

W. F. Tanner has persisted through the years in amassing information on modern sedimentary environments, so that such information could be used in interpreting sedimentary rocks of the geologic column. Hence, not only can ancient and classical geological environments be addressed, but so can modern sedimentary environments that have recently become of paramount importance concerning humankind's treatment of our planet.

It will become apparent that W. F. Tanner has amassed a veritable arsenal of published works. Short of being a scholar of this published work, one might, however, be hard-pressed to discover the motivation, the rationale, and the logic behind his sedimentologic pursuits. A better, more revealing way in which to understand these things, to be able to place them into perspective, is to have the researcher, himself, teach a course on the subject. His offer to teach such a course at the Florida Geological Survey during the 1995 Spring semester provided the opportunity, and motivated the compilation of this work. It is hoped that this document will, to some extent, capture and place into perspective William F. Tanner's approach to sedimentology and granulometry and its environmental ramifications.

James H. Balsillie
March 1995
45 MB

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Copyrighted material appears in this work for which permission to publish was granted from several sources. Acknowlegements are extended to the journal of ***Sedimentology*** for the document:

Socci, A., and Tanner, W. F., 1980, Little known but important papers on grain-size analysis, Sedimentology, v. 27, p. 231-232,

to the journal ***Transactions of the Gulf Coast Association of Geological Societies*** for the document:

Tanner, W. F., 1990, Origin of barrier islands on sandy coasts: Transactions of the Gulf Coast Association of Geological Societies, v. 40, p. 90-94,

and to the ***Journal of Sedimentary Petrology*** (now the ***Journal of Sedimentary Research***) for:

Tanner, W. F., 1964, Modification of sediment size distributions: Journal of Sedimentary Petrology, v. 34, no. 1, p. 156-164,

and the abstract of:

Doeglas, D. J., 1946, Interpretation of the results of mechanical analyses: Journal of Sedimentary Petrology, v. 16, no.2 1, p. 19-40.

Certain illustrations (figures 19, 20, 21, 22, 23, and 35 of this text) and two papers (in which the illustrations were originally published) appear in this document. The papers are:

Tanner, W. F., 1991, Suite statistics: the hydrodynamic evolution of the sediment pool: [In] Principles, Methods and Application of Particle Size Analysis, (J. P. M. Syvitski, ed.), Cambridge University Press, Cambridge, p. 225-236,

and:

Tanner, W. F., 1991, Application of suite statistics to stratigraphy and sea-level changes: [In] Principles, Methods and Application of Particle Size Analysis, (J. P. M. Syvitski, ed.), Cambridge University Press, Cambridge, p. 283-292.

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CONTENTS

APPENDICES

WILLIAM F. TANNER

on

ENVIRONMENTAL CLASTIC GRANULOMETRY

Compiled by
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Chief Editor
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INTRODUCTION

Sedimentology encompasses the scientific study of both sedimentary rocks and unconsolidated sedimentary deposits. Sedimentology is defined by Bates and Jackson (1980) as the ...*scientific study of sedimentary rocks and of the processes by which they are formed* ... and ... *the description, classification, origin, and interpretation of sediments*. They also define granulometry to be the ... *measurement of grains, esp. of grain sizes*. It should be apparent, therefore, that granulometry is a pursuit that, while appearing to be more specialized, has significant impacts on the success of more generalized sedimentologic endeavors.

Unconsolidated sedimentary particles range in size from boulders (e.g., glacially produced products) to colloids. This work deals with quartzose sediment sizes ranging from about -2.0 ϕ (4 mm) to about 5.0 ϕ (0.0313 mm), that is, those sediments whose bulk is comprised of sand-sized material.

At the outset, it is important to understand that the majority, perhaps 90% or more, of sand-sized siliciclastic sediments have been transported and deposited by water. In a recent paper on suite statistics (i.e., a collection of correctly obtained samples from a discrete sedimentologic body), W. F. Tanner (1991a) identified an historical paradigm and asked certain questions pertinent to the objectives of this account.

> *For a century or so the purpose of making grain size measurements was to determine the diameter of a representative particle. This is useful when one is studying reduction in grain size along a river (e.g., Sternberg, 1875). But it is a simplistic approach, and one is entitled to ask: Is the mean diameter the only information that we wish to get? Or does the simplicity of this first step make us think that we have now described the sand pool?*
>
> *When we measure grain size, what do we really want to know? This does not refer to whether we measure the long axis or the short axis of a nonspherical particle, or whether we approximate the diameter by measuring a surrogate (such as a fall velocity). Rather, we ask this question in order to get a glimpse of how far research has come in understanding transport agencies or conditions of deposition, and of the degree to which we might reasonably expect to improve our methods of environmental discrimination.*

Does a set of parameters describing a size distribution for a sample set from a discrete sedimentary deposit allow us to compare the set with some other, that we might recognize a different transport agency or depositional environment? An answer or answers to this question constitutes an underlying objective of this account. However, the question also engenders complexity of the kind that would pique the interest of any researcher. Unfortunately, most of us (even if we were so motivated) are not afforded the luxury to pursue such matters. Rather, we must be content to apply any answers to such a quest in a practical, a practicable, a pragmatic manner, which also constitutes an underlying objective of this work.

In 1795, James Hutton proposed the Uniformitarian Principle, stating that ***...the present is the key to the past***. If this is so, then the corollary that the past is the key to present must also hold true. In addition, a second corollary must be true that the present is the key to the future. It might be submitted, therefore, that in this day-and-age of environmental concern, we might well have a responsibility to place at least equal importance on the corollaries as on the principal. It would appear to be so critical, in fact, that at no time in the history of the discipline has, not just the investigation, but the application of "now geology" or "now earth science" been more important.

This document, while available for unlimited distribution, has not been designed to be a general information document tailored for the layman. It is a quite specific account, which requires some considerable familiarity with granulometry, sedimentology, and statistics associated with probability distributions. It is, therefore, designed for those who require specific information in their approach to environmental concerns, i.e., it is a professional peer group educational/reference document.

One might feel that there is an apparent lack of references to the work of others who have published countless papers on sedimentological matters. Please understand that this document is the result of a short course documenting contributions of one researcher. W. F. Tanner is adamant about giving credit where credit is due. While recording of many references might not be apparent in the following account, they certainly are in his published works to which the reader is referred (e.g., see the appendices).

PARTICLE SIZE AND NOMENCLATURE

In sedimentologic endeavors particulate matter can cover a significant range in size. One scheme, for example encompasses a minimum of five orders in magnitude (Table 1). Note, also, that there is a consistent non-linear progression (square or square-root depending upon where the origin lies) in size and corresponding nomenclature. Using another scale, that of Wentworth (1922), a similar although somewhat different nomenclature-size scale is espoused and commonly used (see Table 2).

Table 1. Basic Paricle Size-Nomeclature Distinctions.

Boulders
----- 256 mm
Cobbles
----- 64 mm
Pebbles
----- 4 mm
Sand
----- 1/16 mm
Silt
----- 1/256 mm
Clay

Table 2. Size Conversions and Particle Nomenclature.

Millimeters (mm)	Phi Units (ϕ)	Wentworth Classification	
		Boulder	
256.00	-8.00	------	
		Cobble	
64.00	-6.00	------	
5.60	-2.50	Pebble	Gravel
4.75	-2.25		
4.00	-2.00	------	
3.35	-1.75		
2.80	-1.50	Granule	
2.38	-1.25		
2.00	-1.00	------	------
1.68	-0.75	Very	
1.41	-0.50	Coarse	
1.19	-0.25	Sand	
1.00	0.00	------	
0.84	0.25	Coarse	
0.71	0.50	Sand	
0.59	0.75		
0.50	1.00	------	
0.42	1.25	Medium	
0.35	1.50	Sand	Sand
0.30	1.75		
0.25	2.00	------	
0.21	2.25	Fine	
0.177	2.50	Sand	
0.15	2.75		
0.125	3.00	------	
0.105	3.25	Very	
0.088	3.50	Fine	
0.074	3.75	Sand	
0.0625	4.00	------	------
0.0526	4.25		
0.0442	4.50		
0.0372	4.75		
0.0313	5.00		Silt
0.0263	5.25		
0.0221	5.50		
0.0039	8.00	------	------
			Clay
0.0002	12.00	------	------
			Colloid

This course addresses ***sand-sized particles***, or in the case of the Wentworth Scale ***sand- and granule-sized particles.***

In addition, this course deals primarily with siliciclastics (i.e., quartz particulate matter). For instance, heavy mineral-laden sediments (e.g., magnetite) behave differently than quartz to forcing elements, and granulometric interpretations will be quite different. Carbonate sediments also produce different results, not because of mass density differences but because of carbonate grain shape divergences. The latter, however, because of the preponderance of $CaCO_3$ sediments in south Florida will receive attention throughout this course.

Numerical representation of sediments is often given in millimeters (mm). There are, however, compelling reasons to use the phi (pronounced "fee") convention. Correct terminology is ***phi units***, the ***phi scale***, or ***phi measure***. Phi units, denoted by the Greek symbols ϕ (lower case) or Φ (upper case) are numerically defined by:

$$\phi = -\log_2 d(mm)$$

where d(mm) is the particle diameter in mm. Conversely,

$$d(mm) = 2^{-\phi}$$

Computational equations for the above which can be easily (e.g., Hobson, 1977) programmed or evaluated using a hand-held calculator, are given by:

$$\phi = -1.442695 \ln d(mm)$$

and

$$d(mm) = INV \ln (-0.69315\ \phi) = e^{-0.69315\ \phi}$$

This course uses and promotes universal use of the phi measure. Reasons for its adoption were forthcoming from the 1963 S.E.P.M. ***Inter-Society Grain Size Study Committee***. They were published by Tanner (1969) and are listed in Table 3.

Table 3. Reasons for Adoption of the Phi Scale (from Tanner 1969).

(1) Evenly-spaced division points, facilitating plotting.
(2) Geometric basis, allowing equally close inspection of all parts of the size spectrum.
(3) Simplicity of subdivision of classes to any precision desired, with no awkward numbers.
(4) Wide range of sizes, extending automatically to any extreme.
(5) Widespread acceptance.
(6) Coincidence of major dividing points with natural class boundaries (approximately).
(7) Ease of use in probability analysis.
(8) Ease of use in computing statistical parameters.
(9) Amenability to more advanced analytical methods.
(10) Fairly close approximation to most other scales, allowing easy adoption.
(11) Phi-size screens are already available commercially.

No other scale is even close to matching this list; most other scales do not have more than three or four of these advantages.

ANALYTICAL CONSIDERATIONS

Sand-sized particulate matter is of such dimension that it responds in a timely manner to aero- and hydrodynamic forces (i.e., wind, waves, astronomical tides, currents, etc.). Conversely, therefore, such sediments can reveal information about how they were transported and, hence, the paleogeography. See, for instance, Socci and Tanner (1980) and text reference to De Vries (1970) of Appendix I.

There are, however, several considerations with which to contend. First, field sampling and laboratory errors do occur. Second, many samples, ... i.e., sample suites, ... are required to verify transport and depositional interpretations and results (e.g., W. F.

Tanner has analytical results for over 11,000 samples from a multitude of transpo-depositional environments each comprised of many sample suites). Third, standardized laboratory and analytical procedures are crucial in order to realize accurate interpretations.

Laboratory Do's and Don'ts

Guidelines for the collection of sand samples are given in Appendix II. Procedures for laboratory analysis of samples are given in Appendix III. The following, however, identify certain issues that deserve special, concerted attention.

Sieving Time

A minimum of 30-minutes is recommended for siliciclastic sediments (longer sieving time is a matter of diminishing returns); see the work of Mizutani as referenced in Socci and Tanner (1980).

Balance Accuracy

Weigh to 0.0001 grams, then round to the nearest 0.001 g.

Splitting

Splitting is "bad news". It is recognized that splitting might be a necessity under some circumstances. However, there should be no more than one split, and to "do without" is even better. See the work of Emmerling and Tanner (1974) referenced in Socci and Tanner (1980).

Sieve Sample Size

Introduce no more than 100 g to the -2.0 ϕ or finer sieve. A larger mass or size will introduce overcrowding. An introductory sample size of 45 g is ideal, but can range from 40 to 50 g.

For instance, for a sample containing 50% quartz and 50% carbonate material, a 100 g sample (maximum size allowable) needs to be sieved first. The CO_3 is then removed with HCl and the siliciclastic fraction resieved. Simple subtraction of the quartz distribution from the total distribution will yield the $CaCO_3$ distribution.

Sieve Interval

Without reservation, it is recommended that 1/4-phi sieve intervals be used in granulometric work.

Analytic Graphical Results

The Bar Graph

The bar graph (Figure 1) is not a rigorous analytical tool; it is for the layman. It is not sufficient to "tell the story" for analytical purposes. There is a better graphical method, however, that "tells the story" with standardized clarity. The bar graph, however, can be presented to facilitate a communicative link leading to the proper form of graphical presentation.

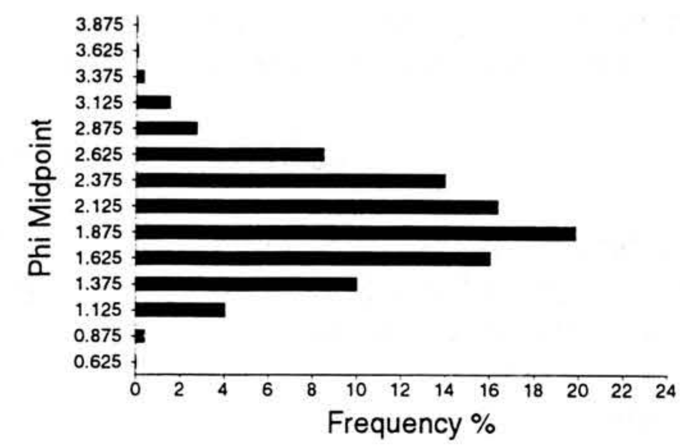


Figure 1. The bar graph.

The Cumulative Graph

This form of graphing (Figure 2) using various types of graph paper (e.g., linear, log cycle, etc.) is too indefinite. Data and paper plotting ordinates may not be evenly spaced leading to possible multiple interpretations (e.g., fitted lines A and B) that can each have significantly high correlation coefficients.

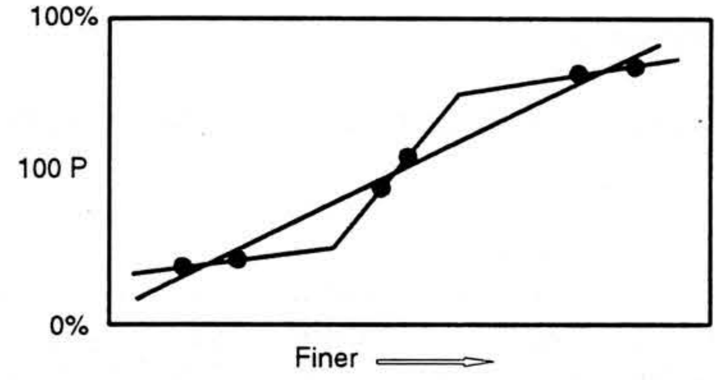


Figure 2. The cumulative graph.

The Probability Plot

This form of plotting (Figure 3) uses arithmetic probability paper. Such paper assures that points will be equally spaced. Ensuing interpolation can then be accomplished with assurance. Such assurance is not always possible using other types of graph paper. Non-parametric parameters, such as the median (50th percentile value), can be located with a good deal of precision. Arithmetic probability paper also allows for the procedure of ***decomposition*** to be discussed later. Moreover, statistical application and arithmetic probability paper constitutes a standardized approach for sedimentologic work. The line on the graph is a true Gaussian (after K. F. Gauss) distribution because it plots as a straight line on probability paper.

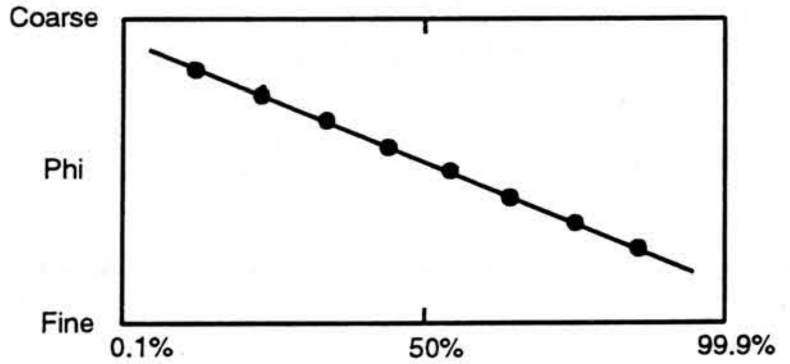


Figure 3. The arithmetic probability plot.

It is more realistically the case, however, that the cumulative distribution for sand-sized siliciclastic samples are comprised of multiple line segments (Figure 4). ***Each segment, in fact, commonly represents a different transpo-depositional process or sediment source.***

RULE: a minimum of three (3) consecutive points are required to identify a segment

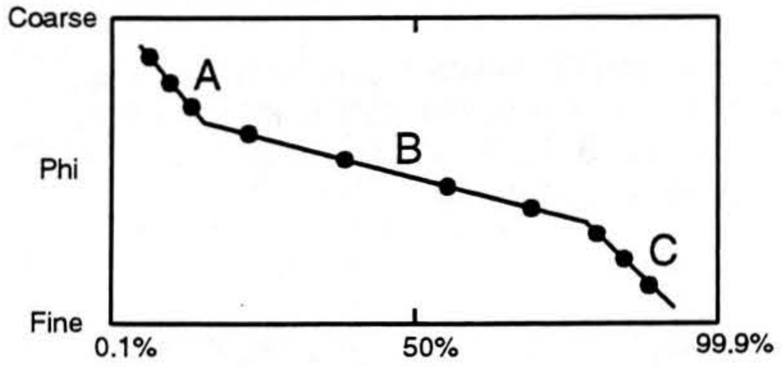


Figure 4. The segmented arithmetic probability plot.

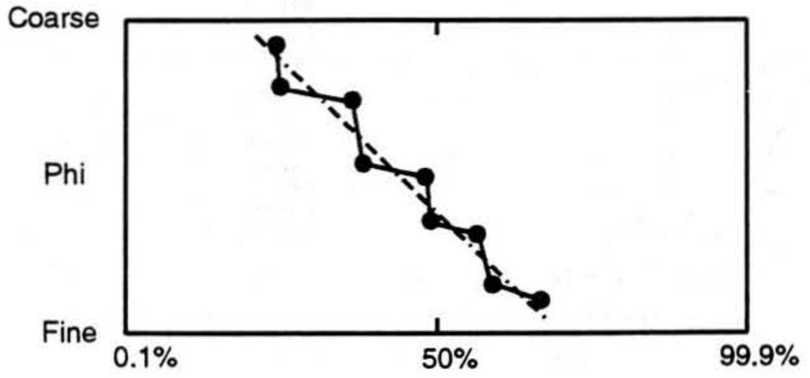


Figure 5. Effect of high energy transpo-depositonal processes.

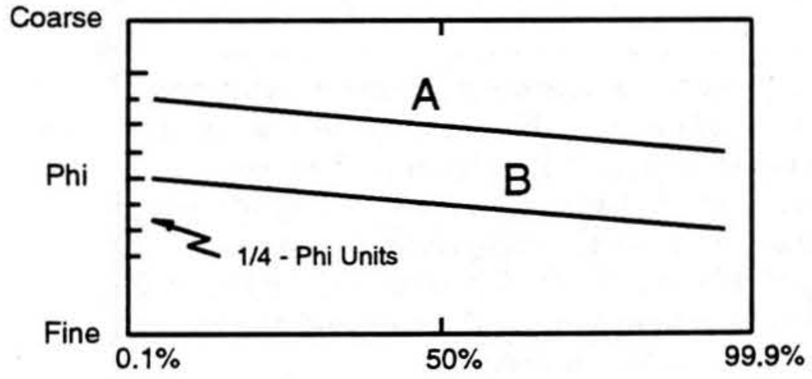


Figure 6. Finer and coarser distributions with identical sorting.

with assurance.

It is to be recognized that some transport processes, such as landslide debris and fluvial flooding, are so rapid that granulometric results are not afforded the time to become Gaussian. However, most eolian and littoral processes provide sufficient time relative to sand-sized range response that analytical granulometric results are allowed to become Gaussian. Hence, transpo-depositional processes can be identified.

High energy fluvial sediment data might appear as plotted in Figure 5. Note that the general trend of the slope of a straight line fitted to the erratic granulometric results is steep, indicating poorly sorted sediments.

However, both eolian and littoral sediment data provide similar results ... they are very well sorted, i.e., along the y-axis the distributions encompass very few 1/4-ϕ units, and line slopes are low. Note: parallel lines of Figure 6 indicate identical sorting, even though sample A has a coarser average size than sample B.

In the example of Figure 7, sample B is better sorted than sample A, even though sample B has a coarser mean.

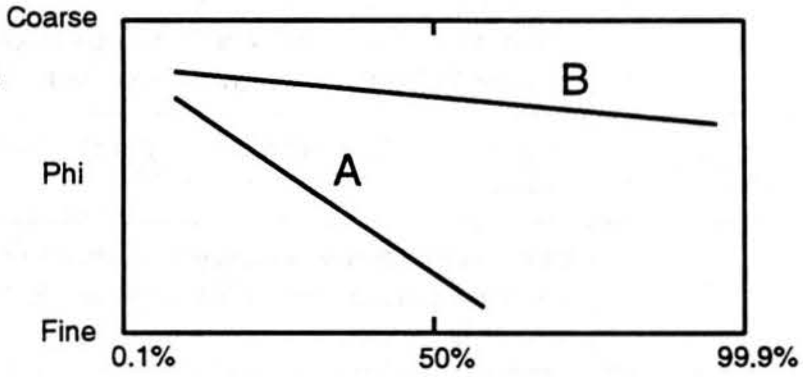
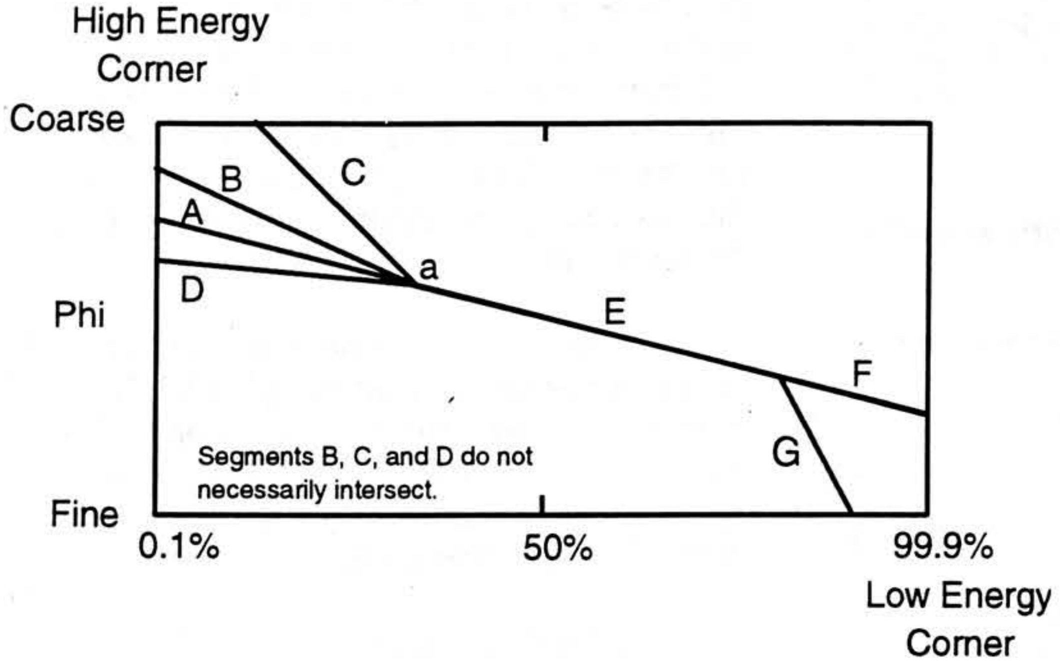


Figure 7. Coarser and finer distributions with different sorting characteristics.

Settling-Eolian-Littoral-Fluvial (SELF) Transpo-Depositional Environmental Identification

Relative relationships of adjoining line segments require relative consideration when interpreting probability plot results, which J. H. Balsillie has termed ***the WFT method of SELF determination***. Consider the generalized plot of Figure 8 for possible combinations of interpretative results. Interpretative descriptions are given in Table 4.



Possible Curve Combinations

AEF
AEG
BEF
BEG
CEF
CEG
DEF
DEG

Figure 8. Basic line segments on arithmetic probability paper.

Table 4. Rudiments of WFT method of SELF determination for line segments of Figure 8.

Segment(S)	Description of Interpretation
AEF	The Gaussian distribution.
B	Indicates that the operating transpo-depositional force element is wave activity; point a, relative to segment E, is termed the ***surf-break***. This slope, which is gentle, represents beach sand ... it occurs no where else ... it is definitive! The higher the slope of segment B, the higher the wave energy. Note that for sand-sized material, the surf-break normally appears for low- to moderate-energy wave climates. For high-energy waves, point a moves off the graph (to the left) and segment B disappears (i.e., the wave energy is over-powering even to the coarsest sand-sized sediment fraction available (Savage, 1958; Balsillie, in press)).
D	Indicates eolian processes; point a is termed, relative to segment E, the ***eolian hump***.
C	Represents fluvial energy ... has a steep slope, the greater the slope the higher the energy expenditure. This segment is termed the ***fluvial coarse tail***, or may represent a pebbly beach.
E	Central portion of the distribution.
G	Is the low energy tail termed the ***settling tail*** and, if present, may indicate lowering of energy for the total distribution or component distributions of the coarser sediments.

Figures 6 and 7 have illustrated how one can identify finer and coarser distributions with different standard deviations (i.e., sorting). For future reference, what of skewness and kurtosis? Figure 9 illustrates how skewness appears on the arithmetic probability plot. Figures 10a and 10b illustrate the effect of kurtosis.

These plots represent simple examples, ..., more complicated results are certainly possible.

It is often advantageous to view concepts using a different approach. Regarding moment measures, consider the following (refer to preceding figures if necessary). First, the mean or average simply locates the central portion of the distribution. Second, the standard deviation on arithmetic probability paper is the slope of the line representing the distribution. Third, the skewness is 0 if the distribution is truly Gaussian (i.e., the often used normal or bell-shaped curve terminology, terms which should be dropped from usage) and, therefore, as much of the distribution lies to the left of the 50th percentile as to the right. Fourth, if the distribution plots as a straight line it is a true Gaussian distribution with a Kurtosis value of K = 3.0. There is published work that identifies the Gaussian kurtosis as 0 or 1; these, however, are but arbitrary definitions determined by subtracting 3 and 2, respectively, from the calculated 4th moment measure.

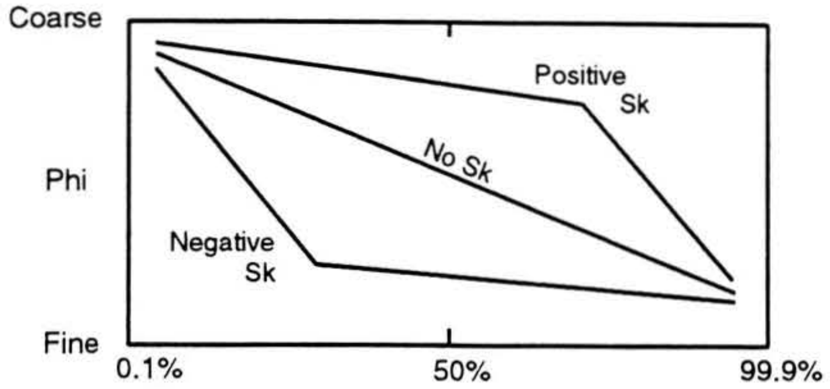


Figure 9. Appearance of skewness on arithmetic probability paper.

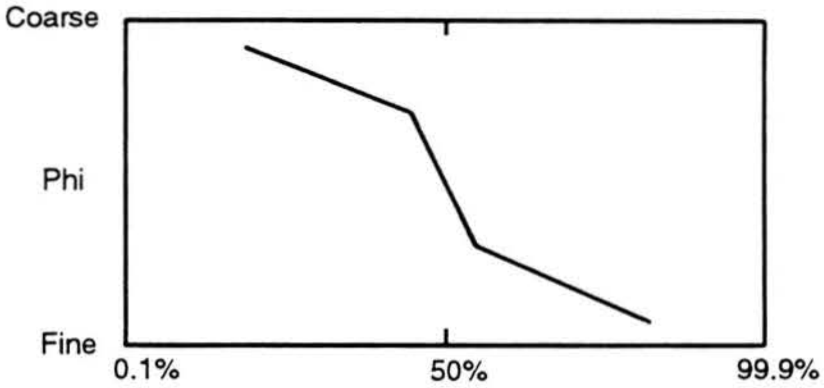


Figure 10a. Appearance of kurtosis on arithmetic probability paper; plot is for a flat-topped (platykurtic) distribution.

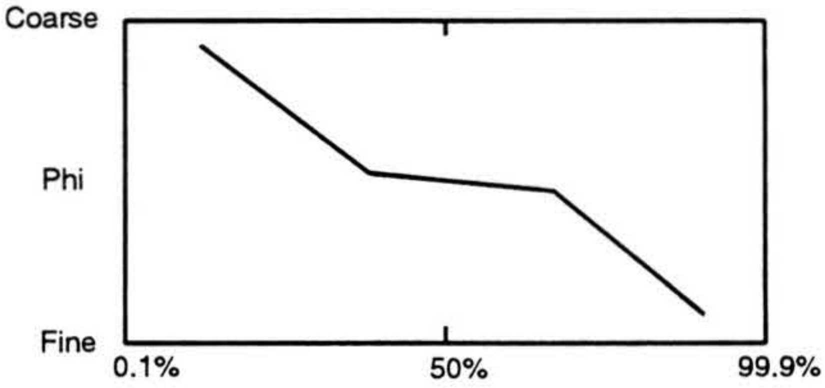


Figure 10b. Appearance of kurtosis on arthimetic probability paper; plot represents a peaked (leptokurtic) distribution.

Line Segments versus Components, and Plot Decomposition

When dealing with plotted sedimentologic data on arithmetic probability paper, one often sees multiple line segments (e.g., Figures 4 and 8). These segments represent, as we have learned, different transpo-depositional processes. They are not distributions in their own right.

There is a common belief espoused in the literature that one can lift out a line segment and examine it on its own to determine low- or mid-level traction loads or suspended load. Such advocates do not understand the aero- or hydrodynamics involved.

Where a probability plot has multiple line segments there are true component distributions or components that can be identified using the process of ***decomposition***. For instance the combined distribution of Figure 11 (multi-segmented curve) is comprised of two components (not three).

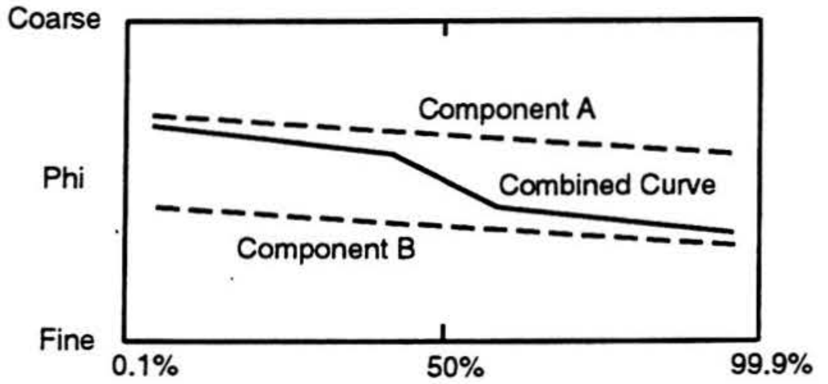


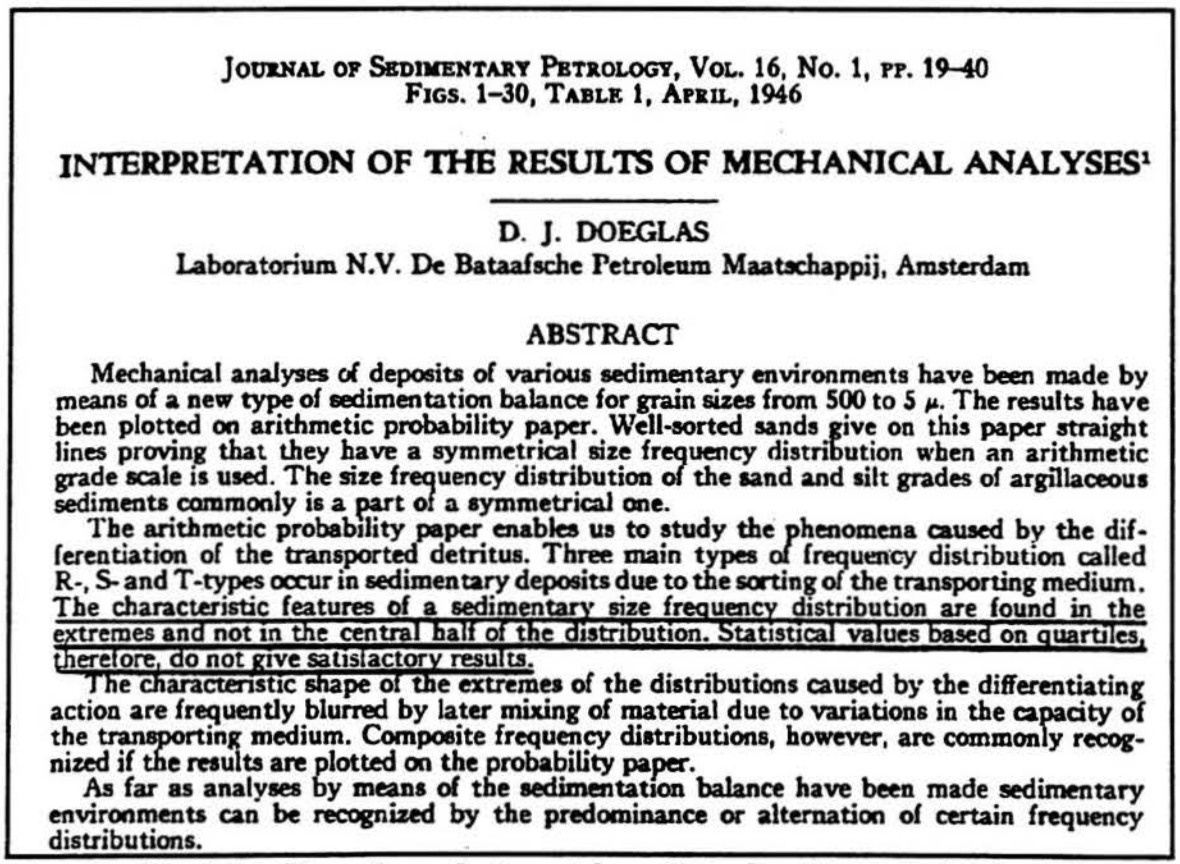
Figure 11. Example of plot decomposition yielding two samples with equal standard deviations and unequal means.

The Key to Probability Distributions

There is a property associated with the Gaussian (or any other) Distribution that is not widely known nor appreciated. However, it is so important that it deserves special identification here. To understand this property will lead to greater clarity as to how statistical distributions are to be viewed, treated, and understood.

> **It is the tails of the distribution which dictate the shape of the central portion of the distribution.**

Most folks assume it is the central portion of the distribution which determines the behavior of the tails ... an assumption that is incorrect. This was first demonstrated to J. H. Balsillie in 1973 by W. R. James (a statistician and geologist, and student of W. C. Krumbein). Doeglas (1946), in an essentially unknown paper, understood this property ... see the underlined text in his abstract (Figure 12).



JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 16, NO. 1, PP. 19–40
FIGS. 1–30, TABLE 1, APRIL, 1946

INTERPRETATION OF THE RESULTS OF MECHANICAL ANALYSES[1]

D. J. DOEGLAS
Laboratorium N.V. De Bataafsche Petroleum Maatschappij, Amsterdam

ABSTRACT

Mechanical analyses of deposits of various sedimentary environments have been made by means of a new type of sedimentation balance for grain sizes from 500 to 5 μ. The results have been plotted on arithmetic probability paper. Well-sorted sands give on this paper straight lines proving that they have a symmetrical size frequency distribution when an arithmetic grade scale is used. The size frequency distribution of the sand and silt grades of argillaceous sediments commonly is a part of a symmetrical one.

The arithmetic probability paper enables us to study the phenomena caused by the differentiation of the transported detritus. Three main types of frequency distribution called R-, S- and T-types occur in sedimentary deposits due to the sorting of the transporting medium. The characteristic features of a sedimentary size frequency distribution are found in the extremes and not in the central half of the distribution. Statistical values based on quartiles, therefore, do not give satisfactory results.

The characteristic shape of the extremes of the distributions caused by the differentiating action are frequently blurred by later mixing of material due to variations in the capacity of the transporting medium. Composite frequency distributions, however, are commonly recognized if the results are plotted on the probability paper.

As far as analyses by means of the sedimentation balance have been made sedimentary environments can be recognized by the predominance or alternation of certain frequency distributions.

Figure 12. The Doeglas abstract (reprinted with permission).

Sieving Versus Settling

Settling tubes have gained popularity because of their time saving capability and, hence, are most often referred to as Rapid Sediment Analyzers (RSA's). There are, however, serious problems associated with RSA's such as drag interference with side walls, and effects of sediment introduction into the fluid, etc. The most serious defect of RSA's, however, involves the production of von Kármán vortex trails by the settling grains.

Theodore von Kármán was born in Hungary in 1881. He was trained as an engineer and became a U. S. citizen in 1936. He was a noted aeronautical engineer and consultant to the U. S. Air Force during the late 1930's and the 1940's. He was recently honored with a U. S. postage stamp.

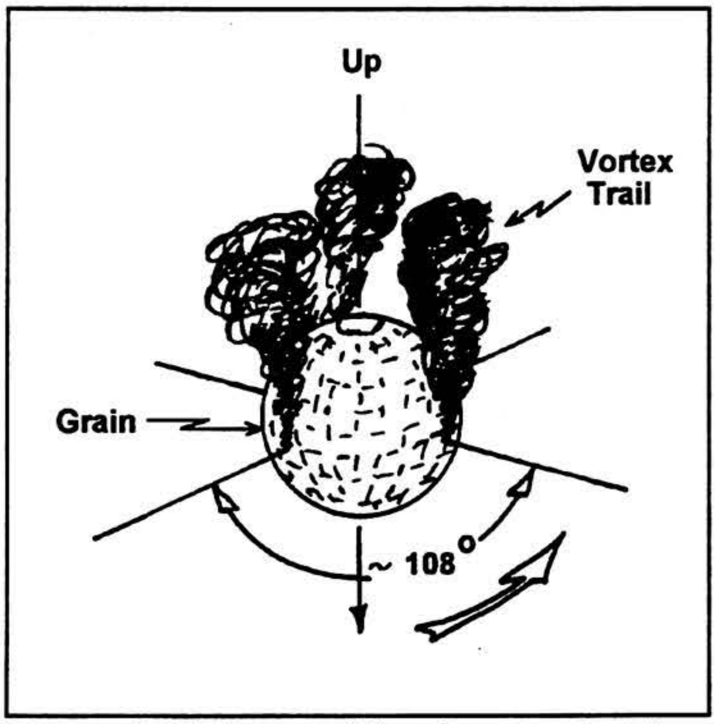


Figure 13. The von Kármán vortex trail phenomenon.

For an automobile or boat wake the von Kármán effect is two-dimensional. For a grain falling in water it is three-dimensional. Each vortex "kicks off" at different times. They are spaced at less than 120 degrees (say 106 to 108 degrees) which causes the entire system to spiral to the bottom (see Figure 13). These vortexes or vortices (latteral effects are 2 to 3 times the sediment grain diameter) affect other grains much in the same manner as the tailgating effect is used in auto racing. The net result is that larger grains entrain smaller trailing grains, increasing the fall velocity of the smaller grains; hence, the smaller grains appear to be larger than they actually are. At the same time, the smaller entrained grains slow the settling velocity of the larger grains, making the latter appear smaller than they actually are.

Bergman (1982) investigated the sieving versus settling problem by not only using sieve and settling tube results, but also microscope size determinations, and he verified the above results. His findings are recounted in Figure 14.

It is also important to note that sieves, at least in the U. S., are standardized. RSA's, however, can significantly vary in equipment type, dimensions, fall velocity mathematics applied, etc. **A most serious problem between RSA's, is that they are not calibrated from laboratory-to-laboratory. Hence, there is <u>no</u> standardized RSA.**

The bulk of the literature concerning the issue, supports sieving over settling devices. The U. S. Army Corps of Engineers, regarding marine sediments and beach restoration design work, recognizes the problems with RSAs. Hobson (1977), in a Coastal Engineering Research Center document, lists some of the common problems as:

> *(a) Failure of the fall velocity equations to account for the effects of varied particle shapes and densities, interference of falling particles with each other,*

Abstract

A comparison of the grain size data derived from sieving and settling techniques of sixty samples from modern sedimentary environments indicates that there exist important differences in the way grain size distributions are perceived by the two methods. A third method of analysis, microscope grain size determination, supports the results of the sieve analysis, indicating that the settling tube has inherent properties which makes it less dependable for grain size studies.

In comparisons of moment measures (sieving vs. settling tube) significant differences were found. The settling tube perceives fine grain sizes coarser than they actually are, and coarse grain sizes finer that they actually are. A compression of the overall distribution of values results. This compression also occurs in individual samples, as indicated by studies of the probability plots. The settling tube fails to detect certain tails (in the distribution) that are indicated by the sieving results. This compression of samples is apparent in the standard deviation sieving vs. settling comparison. The settling tube consistently perceives the samples to be better sorted (lower standard deviation) than is indicated by the sieving results. Results of the skewness and kurtosis comparisons indicate the settling tube is not capable of detecting these small differences in the grain size distribution.

The compression phenomenon caused by the settling tube is thought to have two possible sources. The first, a physical truncation of the distribution by sampling technique, is of varying signficance. The second, a hydrodynamic "truncation", occurs in all samples but may be accentuated with certain changes in the distribution.

Figure 14. Bergman's (1982) Masters Thesis Abstract on grain size determinations.

> *and water turbulence; (b) drag interference between the cylinder walls and the settling particles; (c) the divergent difficulties of accurately timing the rapid fall of larger particles; and (d) various problems associated with introducing the sediment into the fluid.*

Hobson concluded that for practical beach engineering problems, sieve data are the most reliable and reproducible, especially among different laboratories. He also reported that granulometric results from the two techniques (i.e., sieving and RSAs) <u>are not to be mixed</u>.

Moments and Moment Measures

Except for the first moment and the moment measure termed the average or mean, there is a difference between moments and moment measures. Specifically, moment measures are calculated from numerical consideration of moments.

The first moment about zero (m_1) is also the mean or average (μ_ϕ or M_ϕ) calculated according to:

$$\mu_\phi = M_\phi = m_1 = \sum \frac{fx}{n}$$

where x is the class midpoint grain size, f is its frequency (weight percent), and n is the number of classes. Higher orders of moments are computed about the mean as a transcendental progression of the form:

$$m_p = \frac{\sum f(x - m_1)^p}{n - 1}$$

where p is an integer, and m_p is the pth moment about the mean.

Moments required for the evaluation of moment measures are:

$$m_2 = \frac{\sum f(x - m_1)^2}{n - 1}$$

$$m_3 = \frac{\sum f(x - m_1)^3}{n - 1}$$

and

$$m_4 = \frac{\sum f(x - m_1)^4}{n - 1}$$

where m_2 is the second moment, m_3 is the third moment and m_4 is the fourth moment.

The second moment is actually the variance, and the standard deviation moment measure, σ_ϕ, becomes:

$$\sigma_\phi = \sqrt{m_2}$$

The skewness moment measure, Sk_ϕ, is calculated by:

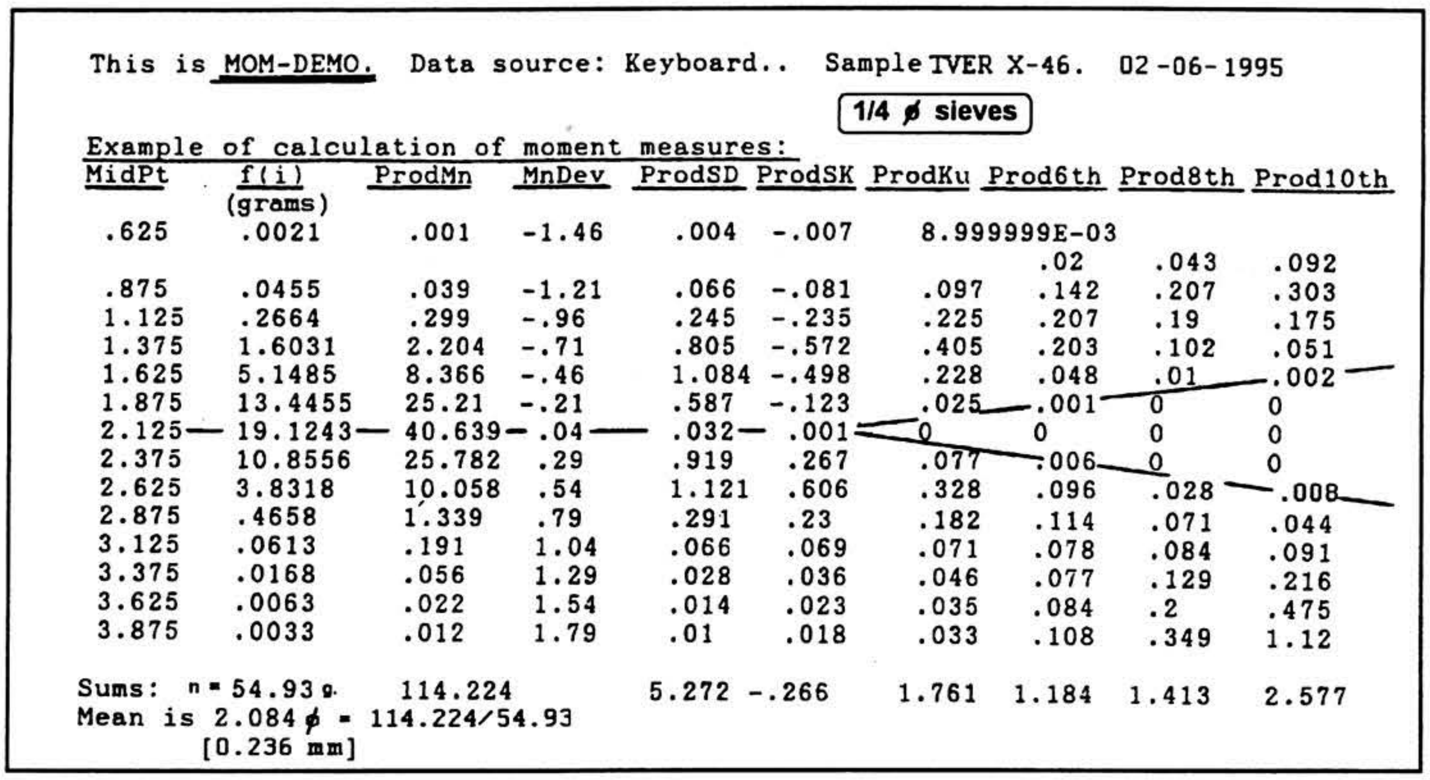
$$Sk_\phi = \frac{m_3}{(m_2)^{1.5}}$$

and the kurtosis moment measure, K_ϕ, is calculated according to:

$$K_\phi = \frac{m_4}{(m_2)^2}$$

An example of moment and moment measure calculations is given in Appendix IV.

It is critically important to understand that higher moment measures progressively describe more about the behavior of the tails of the distribution, as illustrated in the example of Figure 15. The figure illustrates that the higher moment measures are zero near the center of the distribution, whereas non-zero values appear only as the tails of the distribution are approached.



```
This is MOM-DEMO.  Data source: Keyboard..  Sample TVER X-46.  02-06-1995
                                                1/4 ø sieves
Example of calculation of moment measures:
MidPt    f(i)     ProdMn    MnDev   ProdSD ProdSK ProdKu Prod6th Prod8th Prod10th
        (grams)
 .625    .0021     .001     -1.46    .004  -.007    8.999999E-03
                                                          .02     .043    .092
 .875    .0455     .039     -1.21    .066  -.081    .097  .142    .207    .303
1.125    .2664     .299     -.96     .245  -.235    .225  .207    .19     .175
1.375   1.6031    2.204     -.71     .805  -.572    .405  .203    .102    .051
1.625   5.1485    8.366     -.46    1.084  -.498    .228  .048    .01     .002
1.875  13.4455   25.21      -.21     .587  -.123    .025  .001    0       0
2.125  19.1243   40.639     .04      .032   .001    0     0       0       0
2.375  10.8556   25.782     .29      .919   .267    .077  .006    0       0
2.625   3.8318   10.058     .54     1.121   .606    .328  .096    .028    .008
2.875    .4658   1.339      .79      .291   .23     .182  .114    .071    .044
3.125    .0613    .191     1.04      .066   .069    .071  .078    .084    .091
3.375    .0168    .056     1.29      .028   .036    .046  .077    .129    .216
3.625    .0063    .022     1.54      .014   .023    .035  .084    .2      .475
3.875    .0033    .012     1.79      .01    .018    .033  .108    .349   1.12

Sums:  n = 54.93 g.  114.224           5.272  -.266    1.761  1.184  1.413   2.577
Mean is 2.084 ø = 114.224/54.93
        [0.236 mm]
```

Figure 15. Higher moment measures describe the behavior of the tails of the distribution.

For the higher moments, the even moment measures are more meaningful than the odd moment measures. Odd moment measures address asymmetry of the distribution, about which we know relatively little. A comprehensive list of the higher moments and corresponding moment measures (e.g., m_5 is the 5th moment, and mm_5 is the 5th moment measure; there are no descriptive names for mm_5 and higher moment measures) are:

Moment	**Corresponding Moment Measure**
$m_5 = \dfrac{\sum f(x-m_1)^5}{n-1}$	$mm_5 = \dfrac{m_5}{(m_2)^{2.5}} = \dfrac{m_5}{\sigma^5}$
$m_6 = \dfrac{\sum f(x-m_1)^6}{n-1}$	$mm_6 = \dfrac{m_6}{(m_2)^3} = \dfrac{m_6}{\sigma^6}$
$m_7 = \dfrac{\sum f(x-m_1)^7}{n-1}$	$mm_7 = \dfrac{m_7}{(m_2)^{3.5}} = \dfrac{m_7}{\sigma^7}$

$$m_8 = \frac{\sum f(x - m_1)^8}{n - 1} \qquad mm_8 = \frac{m_8}{(m_2)^4} = \frac{m_8}{\sigma^8}$$

How Not to Plot - An Example

Figure 16 illustrates a "bad blunder". First, just what is meant by the "third moment" is uncertain. Second, the meaning of "zone of 2-way beach flow" is open to question. Third, the plotted data are certainly not definitive in delineating the two regions shown. By design or default, the figure certainly does not convince the student that statistics can work. One lesson is that we must be precise in our use and application of analytic numerical methodologies and data presentation. A second lession is that "single sample" data are commonly contradictory.

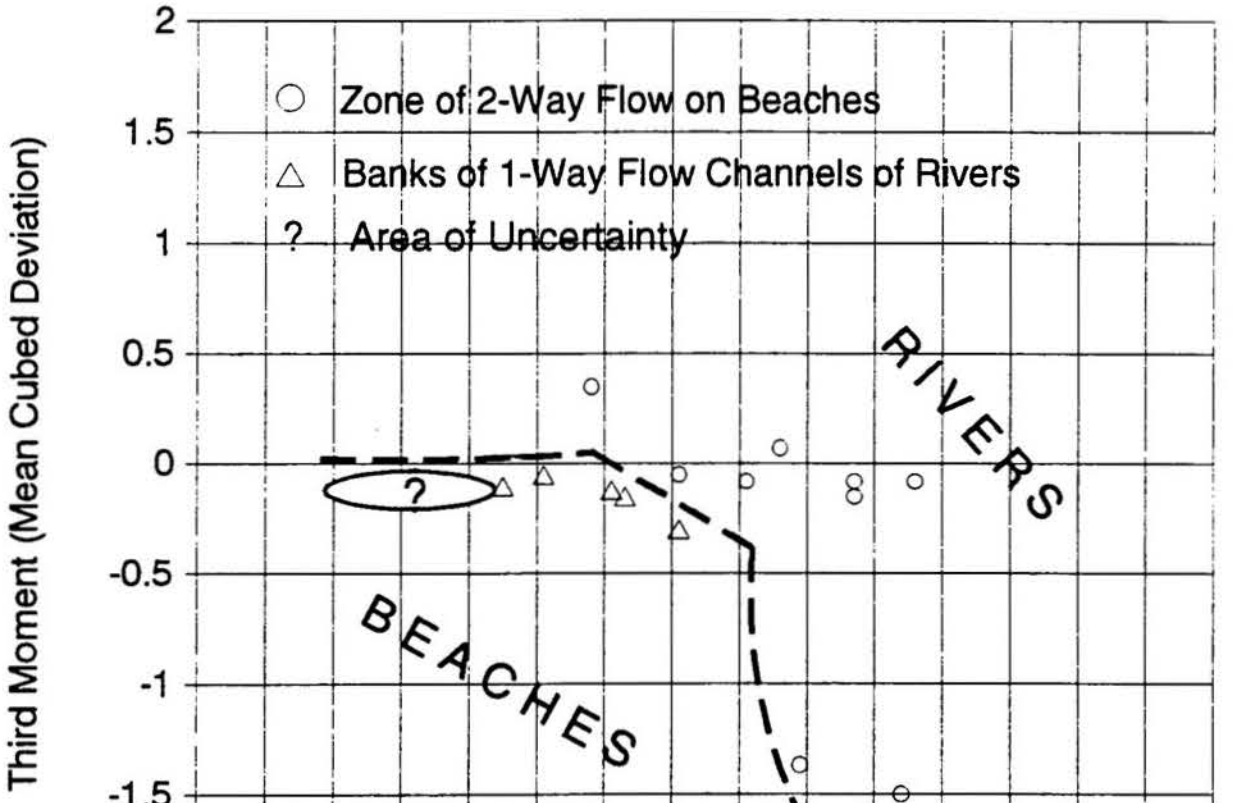


Figure 16. The Friedman and Sanders (1978) plot (replotted). Some 250 individual sample results were originally plotted; only those which disagree with the arbitrarily set division (bold dashed line) are replotted here. The area of uncertainty may contain multiple river sample results (unclear from the original figure).

DETERMINING TRANSPO-DEPOSITIONAL ENVIRONMENTS

Rather than occupying careers as scientists purely for the sake of pursuing scientific discovery, most of us occupy positions where there is a limiting constraint of practicality or pragmatism. Let us apply this to the study of granulometry as it applies to sedimentology and environments of deposition.

Should we be given a siliciclastic sediment sample of unknown or uncertain origin, can we ascertain its transpo-depositional environment? We can certainly address it. Although there is no certainty that we can always provide a solution, in most cases we can. One of the basic issues concerns the hydrodynamics or aerodynamics associated with conditions of sediment transport and deposition.

The Sediment Sample and Sampling Unit

An underlying assumption with such sedimentologic studies is that the field sample we collect is a ***laminar*** sample. This is the ***sedimentation unit*** of Otto (1938, p. 575) defined as ***...that thickness of sediment which was deposited under esentially constant physical conditions***. Similarly, Apfel (1938, p. 67) defined a ***phase*** as ... ***deposition during a single fluctuation in the competency of the transporting agent*** (the reader is also referred to the later work of Jopling, 1964). The sedimentation unit constitutes a narrowly defined event. For instance, it is not deposited by a flood occurring over a period of 3 weeks, but it might be deposited by one energy pulse, with each pulse occurring over-and-over during the flood. It is not known what a sedimentation unit, lamina, or bedding plane is in terms of physical principles. But we can recognize them to some extent. Regardless of the unknowns, we should strive to collect sedimentation unit samples.

In indurated rocks, e.g., sandstones, ground water staining can cause features that appear to be laminae. Drilling can turbidate sediment, causing mixing and disruption of sedimentation units. In many cases, in the field one cannot see the laminae. At other times we can see or sense the laminar bedding in the field, but cannot define it. Where one cannot see the laminae, samples can be taken in a plane parallel to the existing surface if it is determined the surface is the active depositional bedding plane. At other times, a momentary glimpse of bedding planes (due to moisture content, evaporation and associated optics) might occur to aid in sample selection clues. Sampling a sedimentation unit can often be a matter of estimation. However, a multitude of samples termed the ***sample suite*** can aid in assuring sampling completeness.

Suite Pattern Sampling

A suite is a collection of samples that represents a deposit from one transporting agent under one set of conditions and, therefore, must have certain geometric relationships. For instance, it is not practical that 5 samples taken 100 km apart would represent a suite. Do five samples from one river bank or point bar, one beach, or one sand dune that are immediately adjacent to one another (i.e., touching) constitute a suite? By definition, the answer would be yes. However, the preceding two examples are the extremes. Suite samples must be far enough apart to show variation, and yet not spaced far enough apart to represent factors that are not wanted or not related. One can look for the transporting-depositional agent involved and adjust the suite sampling procedure/schedule accordingly.

The number and pattern of suite samples is not etched in stone. For instance, road cuts are where you find them, they are not laid out in advance on a grid. Multi-level, hierarchical sampling schemes are not always possible or the best choice.

One can also collect suite samples as a time series in the rock record "vertical" sequence, although in cross-bedded rocks it can be difficult. In "more recent" unconsolidated sediments comprising a fluvial point bar or beach ridge plain, the time sequence will be in the horizontal direction.

The GRAN-7 Program

While the computer programs W. F. Tanner has developed could be copyrighted as intellectual property, for various reasons he has not, and provides copies of software to all those making request for its use. The GRAN-7 program is based on a program that James P. May wrote a number of years ago called GRANULO. GRAN-7 has been modified and extended in its analytical capability.

Example 1: Great Sand Dunes, central Colorado (Figure 17)

On the first line KIRK identifies the graduate student (Kirkpatrick), the GSD signifies the locality for the Great Sand Dunes in central Colorado. The extension DT$ means that the sample number contains both numeric (DT) and alpha ($) code.

The first panel is the Table of Raw Data. The 5th and 6th columns are the decimal weight percentages or probabilities. That is, multiply by 100 to obtain the values in per cent. These have been computed to 5 decimal places.

The 2nd panel lists moment measures in phi units. They are not graphic measures (which are no longer suitable for use). With the advent of the programmable calculator and Personal Computers, there is <u>no</u> excuse to not use the method of moments and moment measures. In fact, even 40 years ago when we did not have the computing power of today, graphic measures may have not been appropriate in many applications. The 2nd column lists moment measures excluding the pan fraction. The pan, however, may contain various sediments including clay sizes. One may wish to process these using the settling tube. While there are various pan sizes listed, the literature suggests a standard pan size of 5 ϕ for low percentages of the fine fractions (column 3). The 7 ϕ pan (column 6) can significantly weight the pan fraction. NOTE: the GRAN-7 program allows for saving this output so that it can be used in other ensuing software applications.

The relative dispersion (or coefficient of variation) is σ_ϕ/M_ϕ. The smaller the value of the relative dispersion, the "tighter" the distribution. Also, "tail of fines" is the percent of the sample containing the 4 ϕ and finer fraction of the sample. If it is a relatively high percentage, then fluvial sediments are indicated. If it is relatively low, beach or dune sediments are indicated.

Panel 4 is the frequency histogram; panel 5 is the cumulative probability plot with the eolian hump. Note that the cumulative probability plot is much clearer in providing for identification of the eolian properties of the sample than the frequency plot.

Example 2: St. Vincent Island, Florida (Figure 18).

The sample is from St. Vincent Island, taken along the central profile. Note in panel 1 there is no pan fraction. The modal class listed in panel 2 is always the primary mode.

At the 5 ϕ pan, the standard deviation (panel 3) is 0.416 ϕ. This value is not

```
This is GRAN-7.  The data source is kirk-gsd.dt$.   02-24-1995
```

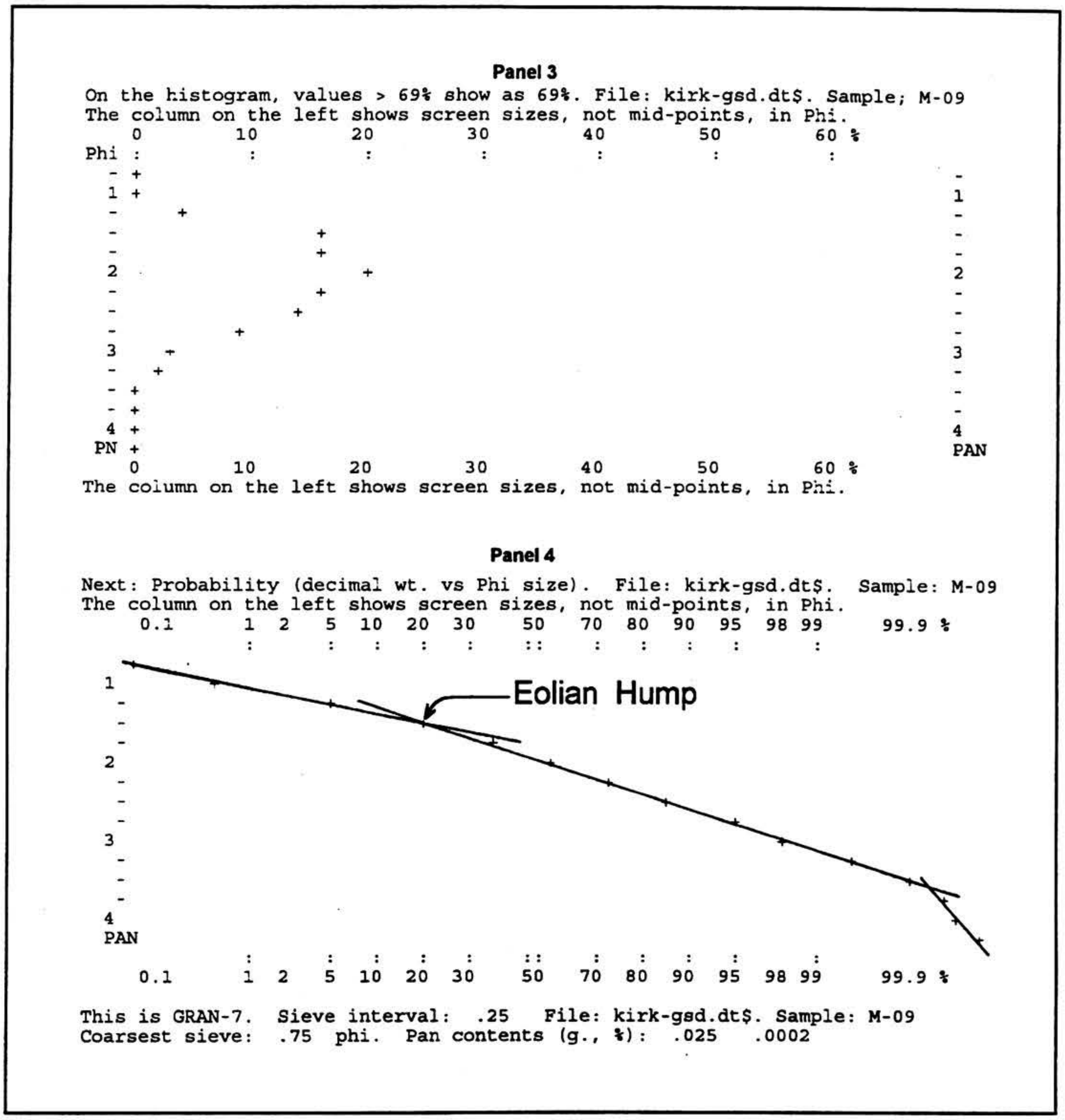
Panel 1

```
This is GRAN-7.  File: kirk-gsd.dt$.  Sample: M-09. Table of raw data:

MidPt(phi)    Sieve(phi)    Wt.(g.)       CumWt(g.)       Wt(Dec.)      Cum.Wt(D)
   .625       .75           .018          .018            .00017          .00017
   .875       1             .397          .415            .00396          .00414
  1.125       1.25          4.059         4.474           .04058          .04473
  1.375       1.5           15.989        20.463          .15988          .20462
  1.625       1.75          16.016        36.479          .16015          .36477
  1.875       2             19.894        56.373          .19893          .56371
  2.125       2.25          16.369        72.742          .16368          .72739
  2.375       2.5           14.007        86.74901        .14006          .86746
  2.625       2.75          8.514         95.26301        .08513          .9526
  2.875       3             2.766         98.02901        .02765          .98026
  3.125       3.25          1.514         99.54301        .01513          .9954
  3.375       3.5           .351          99.894          .0035           .9989
  3.625       3.75          .071          99.965          .0007           .99961
  3.875       4             .013          99.978          .00012          .99974
        PAN                 .025         100.003        .0002          .9999
MidPt(phi)    Sieve(phi)    Wt.(g.)       CumWt(g.)       Wt(Dec.)      Cum.Wt(D)

     Cumulative weight, including pan (if any): 100.003  grams.
```

Panel 2

```
Results calculated by GRAN-7.    File: kirk-gsd.dt$.    Sample: M-09
   Several versions are given below, with the pan fraction either
omitted, or located at different places on the phi scale.    A
widely-used procedure (for moment measures) is to put it at 5 phi.
The relative dispersion is standard deviation divided by the mean.
   The mean, std. dev., etc., are MOMENT (NOT graphic) measures.
Median size:  1.91 phi.  Modal class:  1.75 to  2 phi.


            Exclud.Pan      Pan @ 5      Pan @ 5.5     Pan @ 6     Pan @ 7 phi
Means:         1.948        1.949         1.949        1.949         1.949
Std.Dev.:      .476         .478          .479         .48           .482
Skewness:      .329         .384          .418         .464          .594
JPMaySk:       .164         .192          .209         .232          .297
Kurtosis:      2.674        3.031         3.351        3.841         5.52
Fifth Mom.:    2.793        5.334         8.244        13.294        33.886
Sixth Mom.:    12.37        28.751        53.089       101.485       338.903
Relative dispersion: .244         .246          .246         .246          .248
Dec.Wt. 4 phi & finer: .00032   Coarsest sieve (phi): .75   No. of sieves: 14
   For pan fraction placed at 5 phi, and at 5.5 phi:
SD/Ku: .1577037   .1429424 .  Mn/Ku: .6430221   .5816174
   Pan weight (grams; decimal fraction; %):  .025 ;   .0002 ;   .02
```

Figure 17. Example of granulometric output from GRAN-7 for sample M-09 from the Great Sand Dunes, central Colorado.



Panel 3

```
On the histogram, values > 69% show as 69%. File: kirk-gsd.dt$. Sample; M-09
The column on the left shows screen sizes, not mid-points, in Phi.
```

```
The column on the left shows screen sizes, not mid-points, in Phi.
```

Panel 4

```
Next: Probability (decimal wt. vs Phi size).  File: kirk-gsd.dt$.  Sample: M-09
The column on the left shows screen sizes, not mid-points, in Phi.
```

```
This is GRAN-7.  Sieve interval:  .25   File: kirk-gsd.dt$. Sample: M-09
Coarsest sieve:  .75  phi.  Pan contents (g., %):  .025   .0002
```

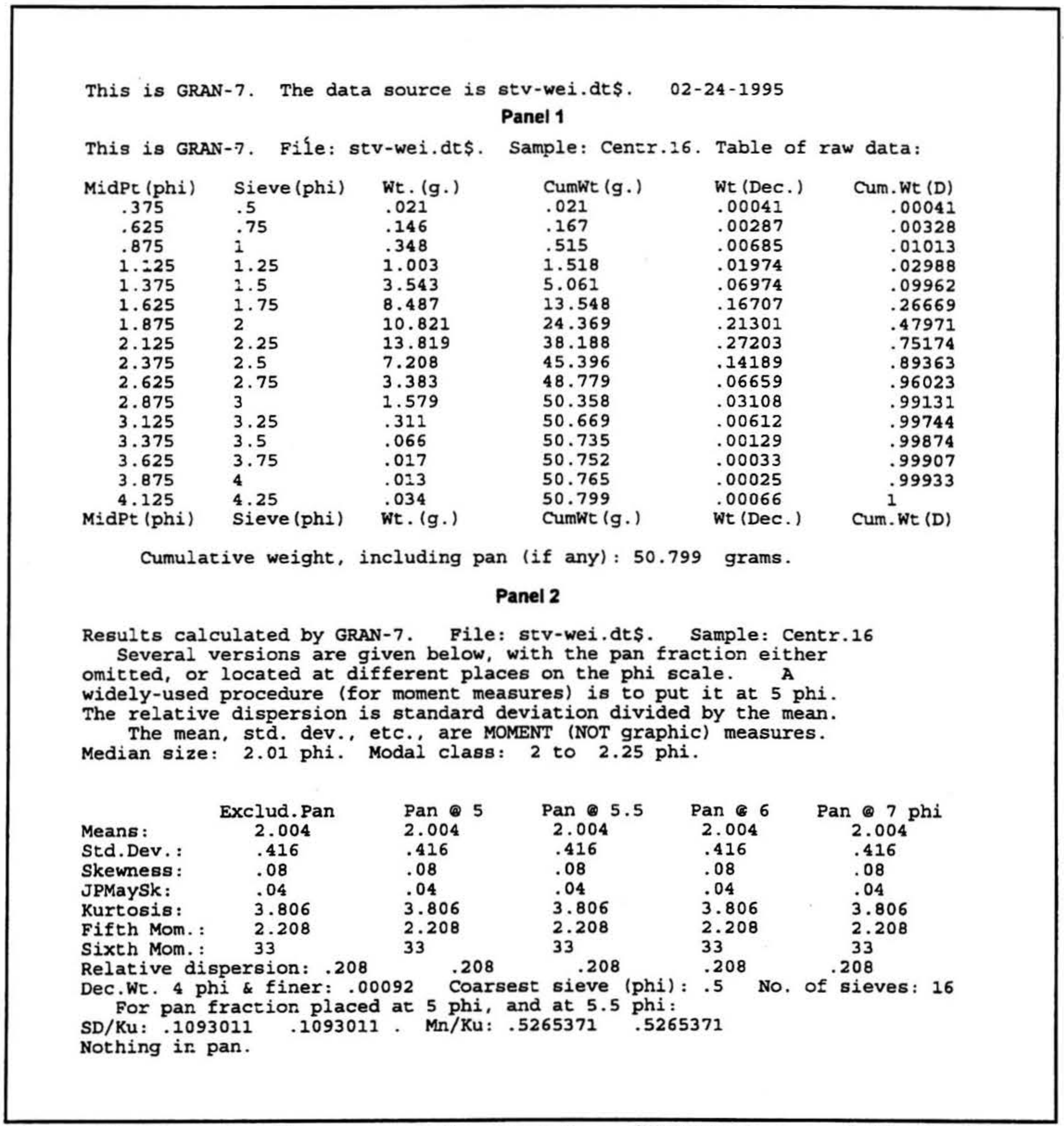
Figure 17. (cont.)

particularly good for a mature beach sand. Mature beaches have σ_ϕ values of from 0.30 to 0.50 ϕ; the lowest σ_ϕ value WFT has seen is about 0.26ϕ.

The cumulative probability plot of panel 4 shows the surf-break. The surf-break inflection point moves with time ... the plot, therefore, is a snapshot in the history of the evolution of the sample. With high enough wave energy or with sufficient time, the inflection point will move to the left and off the plot. Note, also, that there is a tail of fines. Hence, the sample is one reflecting low wave energy. The surf-break occurs at about 4.5% with the settling curve comprised of less than 1% of the sample. Hence, we are looking at only about 5% of the sample. By looking at a multitude of samples we can attempt to clarify our interpretations.

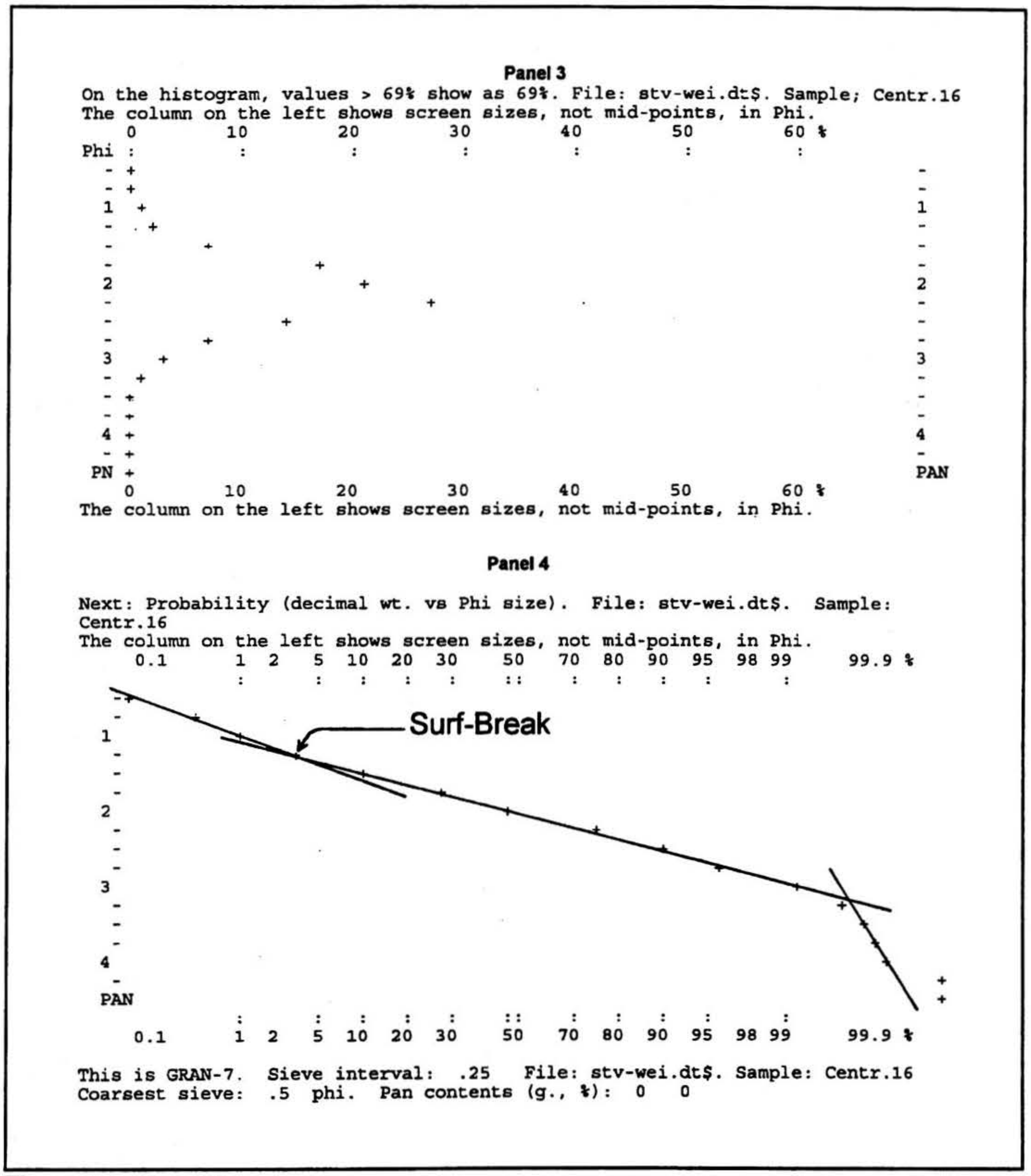
Example 3: The German Darss

The Darss, a German federal nature preserve, is located in Germany fronting on the Baltic sea, just to the east of the old East-West German border. It is attractive to study because it is not subject to open Atlantic Ocean waves. A series of 120 to 200 ridges comprise the plain, although it is not possible to count all the ridges because wind work has been pervasive. The feature has been interpreted by many investigators (~20) to represent



```
This is GRAN-7.  The data source is stv-wei.dt$.   02-24-1995
                                   Panel 1
This is GRAN-7.  File: stv-wei.dt$.  Sample: Centr.16.  Table of raw data:

MidPt(phi)    Sieve(phi)    Wt.(g.)         CumWt(g.)        Wt(Dec.)       Cum.Wt(D)
   .375       .5            .021            .021             .00041           .00041
   .625       .75           .146            .167             .00287           .00328
   .875       1             .348            .515             .00685           .01013
   1.125      1.25          1.003           1.518            .01974           .02988
   1.375      1.5           3.543           5.061            .06974           .09962
   1.625      1.75          8.487           13.548           .16707           .26669
   1.875      2             10.821          24.369           .21301           .47971
   2.125      2.25          13.819          38.188           .27203           .75174
   2.375      2.5           7.208           45.396           .14189           .89363
   2.625      2.75          3.383           48.779           .06659           .96023
   2.875      3             1.579           50.358           .03108           .99131
   3.125      3.25          .311            50.669           .00612           .99744
   3.375      3.5           .066            50.735           .00129           .99874
   3.625      3.75          .017            50.752           .00033           .99907
   3.875      4             .013            50.765           .00025           .99933
   4.125      4.25          .034            50.799           .00066           1
MidPt(phi)    Sieve(phi)    Wt.(g.)         CumWt(g.)        Wt(Dec.)       Cum.Wt(D)

     Cumulative weight, including pan (if any): 50.799  grams.

                                   Panel 2

Results calculated by GRAN-7.   File: stv-wei.dt$.   Sample: Centr.16
   Several versions are given below, with the pan fraction either
omitted, or located at different places on the phi scale.    A
widely-used procedure (for moment measures) is to put it at 5 phi.
The relative dispersion is standard deviation divided by the mean.
    The mean, std. dev., etc., are MOMENT (NOT graphic) measures.
Median size:  2.01 phi.  Modal class:  2 to  2.25 phi.


              Exclud.Pan       Pan @ 5       Pan @ 5.5      Pan @ 6       Pan @ 7 phi
Means:          2.004          2.004          2.004          2.004           2.004
Std.Dev.:       .416           .416           .416           .416            .416
Skewness:       .08            .08            .08            .08             .08
JPMaySk:        .04            .04            .04            .04             .04
Kurtosis:       3.806          3.806          3.806          3.806           3.806
Fifth Mom.:     2.208          2.208          2.208          2.208           2.208
Sixth Mom.:     33             33             33             33              33
Relative dispersion: .208          .208          .208          .208          .208
Dec.Wt. 4 phi & finer: .00092   Coarsest sieve (phi): .5   No. of sieves: 16
   For pan fraction placed at 5 phi, and at 5.5 phi:
SD/Ku: .1093011    .1093011 .  Mn/Ku: .5265371    .5265371
Nothing in pan.
```

Figure 18. Example of granulometric output from GRAN-7 for sample Centr. 16 from St. Vincent Island, Florida.



Panel 3

```
On the histogram, values > 69% show as 69%. File: stv-wei.dt$. Sample; Centr.16
The column on the left shows screen sizes, not mid-points, in Phi.
```

```
The column on the left shows screen sizes, not mid-points, in Phi.
```

Panel 4

```
Next: Probability (decimal wt. vs Phi size).  File: stv-wei.dt$.  Sample:
Centr.16
The column on the left shows screen sizes, not mid-points, in Phi.
```

```
This is GRAN-7.  Sieve interval:  .25   File: stv-wei.dt$. Sample: Centr.16
Coarsest sieve:  .5  phi.  Pan contents (g., %):  0   0
```

Figure 18. (cont.)

a dune field. Ul'st (1957) trenched the Darss ridges and found low-angle, fair-weather, beach-type cross-bedding and concluded that they were beach ridges (i.e., wave deposited) with a top layer of eolian decoration. Zenkovich (1967), in his text ***Processes of Coastal Development***, noted that Ul'st investigated the Darss ridges, but persisted to view them as dunes. [Aside: one should be very careful when using this textbook ... it is written in such a manner that one can be easily misled.] Many of the dune proponents visually examined only the surface and, of course, found eolian evidence. Harald Elsner, at W. F. Tanner's request, sampled the ridges where eolian reworking appeared minimal then trenched 30 to 50 cm deep where the samples were taken. A total of 16 samples were sent to W. F. Tanner for analysis, the results of which are described in detail in Appendix V. Of the 16 samples, 12 had the definitive surf-break. Only one had the eolian hump. Not one sample plotted showed fluvial conditions, 5 samples plotted as swash, and 7 as settling. The features are, therefore, beach ridges and not dunes.

Example 4: Florida Panhandle Offshore Data

Arthur et al. (1986) reported on offshore sediments along the northwestern panhandle Gulf Coast of Florida. Samples were taken from 1 to 15 km offshore. Can the surf-break be found in sediments found in fairly deep offshore coastal waters? There are two important considerations here: 1. How deep can storm waves affect bottom sediments? and 2. Has sea level rise during the last 15,000 to 20,000 years resulted in an onshore shoreline transgression? The offshore sand sample data were analyzed and the surf-break inflection was found for most of the samples (see Tanner, 1991b, Appendix VIII, p. 118).

Example 5: Florida Archeological Site

W. F. Tanner was asked to assess sediment from an archeological site on U. S. 90 just west of Marianna, FL, where there are several "Indian mounds". The State Archeologist wanted to know why they were composed of 98% quartz sand, since such mounds are normally comprised of shell material. The mounds were trenched. No bedding was found. Sample analysis showed the surf-break. The mounds probabily represent marine terrace deposits reworked by eolian processes. That is, some degree of eolian reworking may not always destroy the surf-break character of the sediments. Such destruction of the indicator would require higher energy levels and/or time.

Example 6: Origin of Barrier Islands (Appendix VI)

Much of the work on the origin of barrier islands is in error (refer to Appendix VI entitled *Origin of Barrier Islands on Sandy Coasts* (Tanner, 1990a; Appendix VI). Tanner (1990a; Appendix VI, p. 96) presents a list and discussion of common origin hypotheses. Felix Rizk (Appendix VI, p. 97, 2nd column, 2nd paragraph down) trenched and took 10 or more samples from each of the two nuclei (i.e., initial vestiges of island formation). Means of the samples from the nuclei were 0.24 mm and 0.22 mm with a slight coarsening trend in one direction. It is generally homogenized sand, all of which looks alike. Standard deviations (Appendix VI, p. 97, col. 2, paragraph 4) for the two areas were statistically the same. However, these numbers which have typical values for beach sand are a little larger than the adjacent, younger non-nuclei sediments. Hence, the sorting of the younger non-nuclei sand has improved with time. We can draw the inference that this area has been reworked by waves. With assurance, neither nucleus was a dune, nor was it deposited by a river. Skewness values (Appendix VI, p. 97, col. 2, paragraph 5) are slightly negative. These values are typical of beach or river sand deposits, but rivers can be ruled out by the above. They are absolutely not dunes or deposits settling from water. Kurtosis values (Appendix VI, p. 97, col. 2, paragraph 6) are low to moderate, indicating low to moderate wave energy levels. Altogether, (Appendix VI, p. 97, col. 2, paragraphs 6 and 7) the nuclei were formed by the same agencies that formed everything else, that is, by wave activity.

This account is not advocating that barrier island formation, in isolated cases, cannot occur for some of the hypotheses listed, for example, drowning of dunes. However, the above example and data for other locales (e.g., St. Vincent Island (Appendix VI, p. 99, figure 1), and Johnson Shoal off of Cayo Costa (Appendix VI, p. 99, figure 2)) suggest that for the majority of cases, barrier island formation occurs because of small sea level changes of one or two meters and accompanying wave and swash activity.

Sample Suite Statistical Analysis

Please refer to Appendix VII entitled *Suite Statistics: The Hydrodynamic Evolution of the Sediment Pool* (W. F. Tanner, 1991a, [In] *Principles, methods, and application of particle size analysis*. Cambridge University Press).

Let us assume that we have 20 samples taken 10 m apart and representing some depositonal time frame, say, 10 years. Do not mix Cambrian with Devonian samples and expect to make sense of the results.

For years in statistical pursuits large sampling statistics required the number of samples, n, to be 30 or more. That is not required in granulometric work. For instance, n = 15 or n = 8 may be quite enough. There is a way of checking the required value of n so that we do not have to be uncertain about it. A desirable number of sediment samples for a suite is commonly from 15 to 20 samples.

Also, what is a reasonable sampling distance? There is a no specified distance, except for the absurd. But, again, bear in mind that the field worker is a "prisoner" of what is available ... one does the best that he or she can.

Suite statistics, for our 20 samples above, might, for instance, yield 20 means, 20 standard deviations, 20 skewness values, 20 kurtosis values, 20 fifth moment measures, 20 sixth moment measures, and the tail of fines. This encompasses 140 data points. If we use the same parameters in a suite analysis, 49 suite statistics will result, more if we recombine the original individual sample data. Therefore, there are many data with which to work.

What we are interested in is a way to examine the behavior of sample suites relative to the individual samples. The plot of Figure 16 is an example of horrible scatter (see Tanner, 1991; Appendix VII, p. 104, second column for further discussion). There are procedures available to permit one to break a large number of samples into smaller groups. In addition, one can conduct repetitive recombinations of groups in order to inspect for improved grouping of one or more of the descriptive moment measures (e.g. mean, std. dev. ... 6th moment measure, etc.).

Please review from Appendix VII:

- last paragraph of page 102,
- Control factors - air versus water of page 103,
- Trapping phenomena beginning on the last paragraph, 1st column of page 103,
- Bivariate plots on page 104.

Tail of Fines Plot: [Appendix VII, p. 105, figure 16.1].

This is a plot of the suite means, μ, and suite standard deviations, σ, of the weight percents that are 4 ϕ and finer (Figure 19).

The Tail of Fines Plot is successful because it is dependent on the aero- and hydrodynamics. The suite mean separates a large, new sediment supply (i.e., river or closed basin sediments) from winnowing or sorting products (i.e., beach and dune sediments). The suite standard deviation separates BAFS (i.e., mature beach and near-shore sediments) and large mass density differences (i.e., dune sediments) from settling and winnowed products. It is sensitive enough to distinguish between mature beach and mature dune sands, because the number of transport events for beaches is 10^5 or 10^6 times as large as it is for dunes during the annual period.

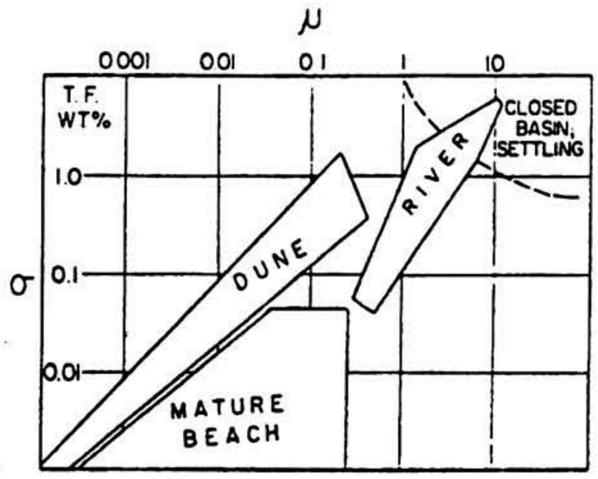


Figure 16.1. The tail-of-fines diagram. The means and standard deviations of the weight percents on the 4 ϕ screen and finer are shown here. Four fairly distinct number fields appear, as labeled above, with relatively little overlap. Many suites plot neatly in a single field. In certain other cases the apparent ambiguity may be useful; for example, a point at a mean of 0.01 and a standard deviation of 0.017 might indicate either dune or mature beach, and not formed in a closed basin. This diagram commonly gives a "river" position when in fact the river was the "last-previous" agency, but not the final one.

Figure 19. Tail-of-Fines Plot. (From Tanner, 1991a).

The Variability Diagram: [Appendix VII, p. 105, figure 16.2].

This plot is also based on suite statitics (Figure 20) where:

σ_μ = standard deviation of the individual sample means, and

σ_σ = standard deviation of the individual sample standard deviations.

Why is the lower-left to upper-right band so broad? One might argue that there is lot that we do not know about this diagram. Richard Hummel of the Alabama State Survey has done some very good work with this plot, and suggests we are missing some transporting agencies.

The diagonal lines stop in the middle. Samples can, therefore, overlap and one may not know which agency is the primary transporting agent. Other plotting tools, therefore, would have to be consulted to clarify which is the transporting mechanism.

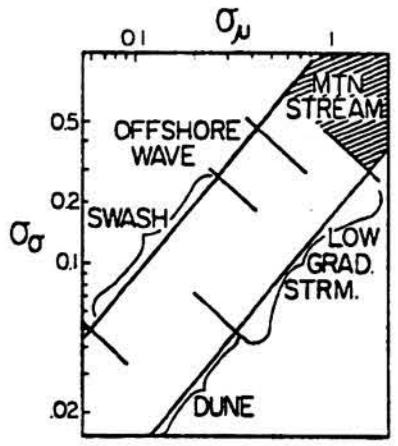


Figure 16.2. The variability diagram, showing the suite standard deviation of the sample means and of the sample standard deviations. Except for the extremes, the plotted position indicates two possible agencies (such as swash or dune). The decision between these two can be made, in most instances, by consulting other plots (such as Fig. 16.1). This diagram considers specifically the variability, within the suite, from one sample to the others.

Figure 20. The Variability Diagram. (From Tanner, 1991a).

Skewness Versus Kurtosis Plot: [Appendix VII, p. 106, figure 16.3].

Suite averages for the skewness (Sk) and Kurtosis (K) are plotted in this diagram (Figure 21).

River ....
Beach ———
Eolian & Settling -------

Beach and river sands tend to be skewed to the coarse, i.e., Sk < 0.1.

Settling tail or closed basin sediments are skewed to the fine, i.e., Sk > 0.1. Eolian sands also occur for Sk > 0.1 as explained in text (Appendix VII, p. 106, last paragraph, 1st column).

There is no guarantee that this plot will produce definitive results. That is why a number of different plotting diagrams for process identification have been compiled. Collective consideration of them together will more nearly allow one to ferret out the most plausible explanation. Using these plots one can tally the results, for example see Table 5. While confusing results can certainly occur, it is generally the case that the tally is never close, such as identification of the beach transpo-depositional mechanism above.

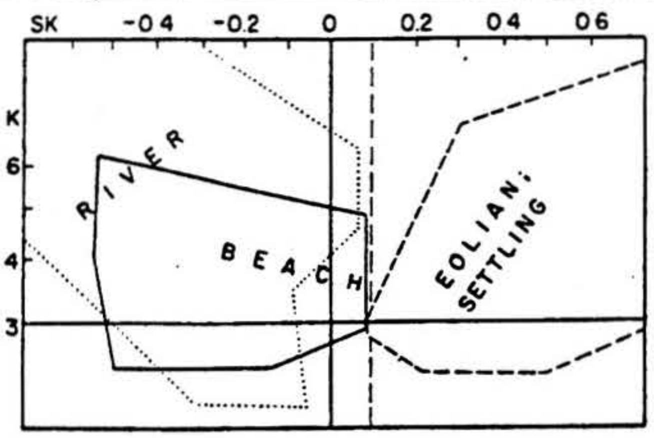


Figure 16.3. Skewness vs. kurtosis. The suite means of these two parameters are used. Positive skewness, as used here, identifies a geometrically distinctive fine tail; if there is also a distinctive coarse tail, it is the smaller (weight percent) of the two. The closed basin (settling) environment typically produces an obvious fine tail, much more so than beach or river sands. Eolian sands commonly have, instead of a well-developed fine tail, a feature called the *eolian hump* (cf. Fig. 16.5), which the skewness indicates in the same way as it does a distinctive fine tail. Therefore the two tend to plot together. Negative skewness identifies a distinctive coarse tail, either fluvial coarse tail (large *K*) or surf "break" (= kink in the probability plot; *K* in the range of 3–5 or so). Many river and beach suites appear in the same part of the diagram but are ordinarily easy to identify by using this figure first and then the tail-of-fines diagram (Fig. 16.1).

Figure 21. Skewness vs. Kurtosis Plot. (From Tanner, 1991a).

Table 5. Tallying the granulometric results.

River	Beach	Settling	Dune
x	X x X X	x X	X

Diagrammatic Probability Plots: [Appendix VII, p. 108, figure 16.5].

These plots are for individual samples (Figure 22). Note the eolian hump of sample 2. Question: the swash zone sand dries out and a relatively strong wind removes the top layer and transports it 4 m down the beach where it is deposited. At what split second in time did it quit being beach sand to become eolian material? That is, is there any place where one can identify a point in time between the two deposits where the sediment changed from beach to eolian sand? The answer should clearly be NO! There is no razor-sharp demarcating line or point ... it is gradational. Wind tunnel laboratory results confirm the process. In fact, the results are normally clearer than one might expect, given that the philosophical concerns are not clear. One has to realize that the previous transpo-depositional history of a sample is bound to characterize any sample and to show up in these plotting tools. Even so W. F. Tanner has been delighted with the success of these analytical diagrams.

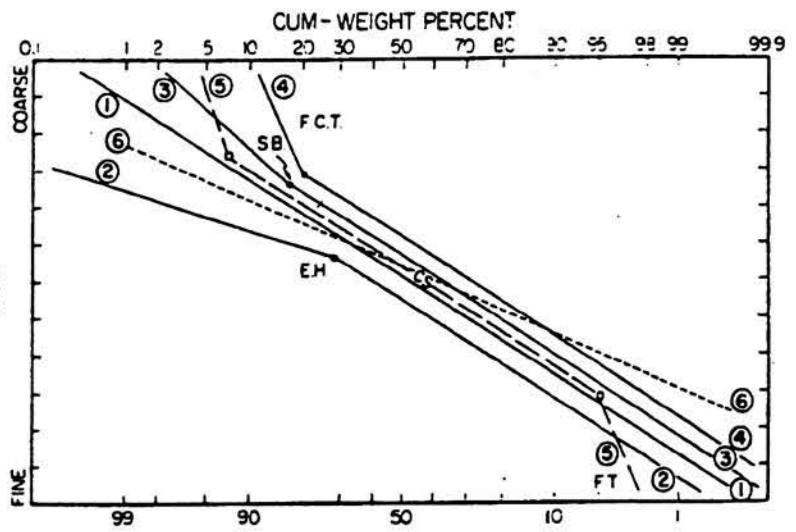


Figure 16.5. Diagrammatic probability plots. (1) The Gaussian, rare among sands. (2) The distinctive eolian hump (E.H.) is common, but not universal, in dune sands, and so far has not been observed in other sands that did not have any previous eolian history. (3) The surf break (S.B.) has been demonstrated to form in the surf zone, as the sorting improves. (4) The fluvial coarse tail is geometrically distinctive, but cannot be distinguished in every case from the surf break. (5) This curve has both a fluvial coarse tail and a fluvial fine tail; the central segment (C.S.) is the line between the two small squares. However, it is not the modal swarm (see text). (6) The modal swarm (a grain size concept, not a graphic one) obtained by subtraction from the original distribution; it shows the actual size distribution of the central segment (graphic device) of line 5. Lines of these kinds help one visualize the effects summarized in the bivariate plots.

Figure 22. Diagrammatic Probability Plots. (From Tanner, 1991a).

Aside: sampling of marine sediments is not easy. It is highly difficult to sample laminae. Grab samples from ship board are really not ideal. Rather, an experienced bottom diver is required.

The Segment Analysis Triangle: [Appendix VII, p. 106, figure 16.4].

This is a very powerful tool. It cannot be plotted by computer program; data must be subjectively determined and then plotted (see Figure 23). Values are determined from the probability plot (see Figure 24) for each sample. There must first be identified a centrally located absolutely Gaussian, straight-line segment. Now, we want to identify the weight percentages for the coarse tail (CT) and fine tail (FT). The value to be plotted on the Segment Analysis Triangle, SA$_{val}$, is calculated as:

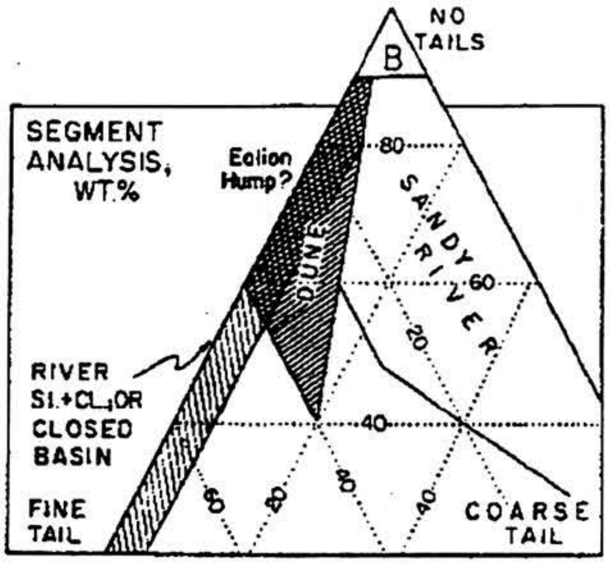


Figure 16.4. The segment analysis triangle. The procedure for picking segments and obtaining the necessary numbers is outlined in the text. The apex is characterized by very small or negligible distinctive tails ("no tails"), and the base (not shown) connects distinctive coarse tail (to the right) with distinctive fine tail (to the left). Four different environments are distinguished reasonably clearly, except for one area of overlap; in this area, one examines the probability plots for the eolian hump in order to see which of the two is indicated.

Figure 23. The Segment Analysis Triangle. (From Tanner, 1991a).

$$SA_{val} = B - A$$

where A and B are the respective weight percentages.

Labels on the Segment Analysis Triangle include SI for river silt and CL for river clay, or a closed basin such as an estuary, lake or lagoon, etc. Note that the river SI and Cl and closed basin sediment field overlaps the dune sediment field. If the eolian hump does not show up in the probability plots of the samples, it is unlikely that the suite represents dune sediments.

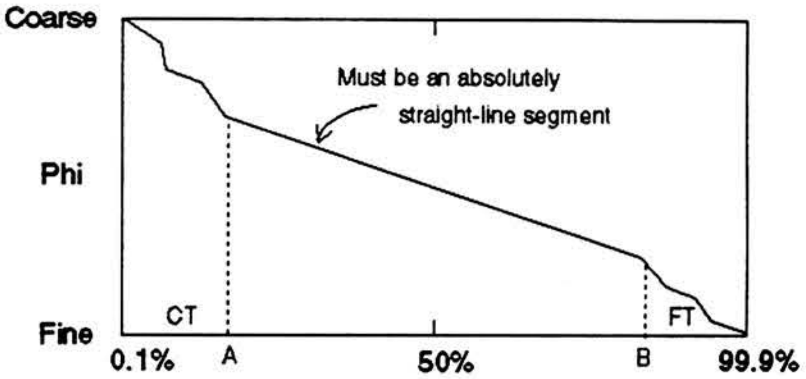


Figure 24. Determination of values for A and B for evaluation of the Segment Analysis Triangle.

Approach to the Investigation

It should be obvious to the geologist with any experience that he or she needs all the help that he or she can get. There are often no easy answers in pursuing matters of a technical nature, particulary when we first are introduced to the field locatity that might be of interest. There are, when undertaking such an investigation, some questions that we would like to address.

The Field Site:

The first endeavor is to try to identify just what we are dealing with. Examples might include:

B	-	Beach
MB	-	Mature Beach
ED	-	Eolian Dune (or ash, loess, etc.)
GLF	-	Glacial-Fluvial Deposit

S - Settling Basin
U - Unknown

The stratigraphic column, both the target and non-target stratigraphy, can often be useful to provide clues to the problem at hand. Classical geology dictates that the present is the key to the past. In many cases, the corollaries that the past is the key to the present and both the past and present are the key to the future yields successful results. It is also important that any non-recognizable aspects of the stratigraphy are noted.

The Paleogeography:

The second pursuit is to make a statement or statements about the paleogeography of the site, if that is at all possible. For example, if the deposit is identified as beach material it would be highly useful to discern in which direction lay the upland and in which direction lay the sea. Other similar determinations should be made depending upon the paleoenvironment identified.

Cross-plots, such as those of Figure 19 through 23, are useful tools to identify transpo-depositional sediments such as those above, ..., e.g., B, MB, ED, GLF, and S.

Hydrodynamics:

It is straighforward procedure to plot our data using a geological mapping format (e.g., grain size, heavy mineral content, etc.). Remember, however, that when dealing with sand-sized sediments, the central portion of the distribution tells us little about the sample. It is, rather, the tails of the distribution that provide us with useful information... a lesson Doeglas taught some 50 years ago!

By way of contrast, envision the scenario of the western flank of the Andes Mountains in which a talus slope near the upper base is comprised of 1 to 2 meter diameter boulders. Farther to the west and down-slope on the river fan, sediment size diminishes greatly. The sediment size gradient, therefore, is highly significant. For our endeavors, however, such a gradient is not available, since we are working within the sand-sized range. If we take our clue from Doeglas and what we have learned about the tails of the sand-sized distribution and moment measures, we need to be looking at the 3rd moment measure or skewness, and the 4th moment measure or kurtosis. Specifically, as it relates to hydrodynamics, let us look at the kurtosis.

The Kurtosis

The bulk of the work on the relationship between hydrodynamics and kurtosis has been conducted on beaches, in particular, Florida beaches. Specifically, kurtosis and hydrodynamics can be related in terms of the energy levels associated with the hydrodynamics. Hydrodynamic force elements inducing a sedimentologic response include characteristic wave energy levels for coasts, long-term sea level rise, seasonal changes, and short-term storm tide and wave impact events.

Kurtosis and Wave Energy Climates:

Let us denote average wave energy in terms of wave height which, according to classical Airy or Small Amplitude wave theory, is given by:

$$E = \frac{\rho_f g}{8} H^2$$

in which E is the wave energy density per unit surface area, ρ_f is the fluid mass density, g is the acceleration of gravity, and H is the average wave height. Hence, simply put for diagrammatic uses, $E \propto H^2$. Let us also denote the kurtosis as K. Consider the following five (5) example cases.

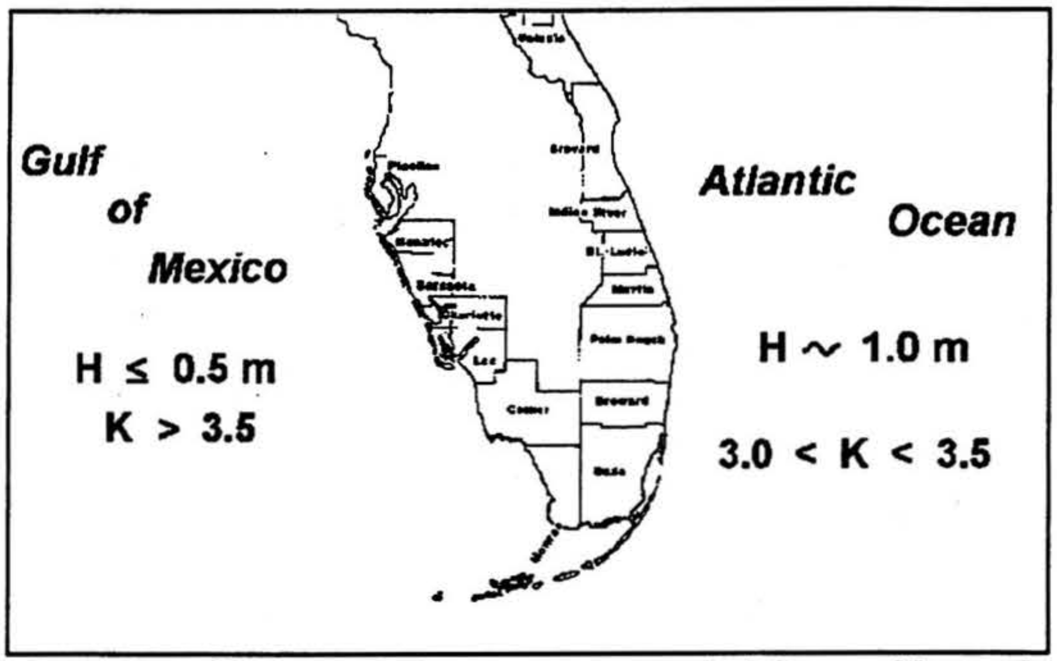


Figure 25. Characteristic average wave heights and kurtosis values for the coasts of lower peninsular Florida.

Case 1. The Lower Peninsular East and West Coasts of Florida. The prevailing wind direction for the lower peninsula of Florida is from the east. Noting that the Atlantic has a larger fetch (i.e., length over which the wind acts to generate gravity water waves) than the Gulf of Mexico, we would expect to find larger waves along Florida's east coast, lower waves along the lower Gulf Coast (Figure 25). In fact, the average wave height along the east coast is typically about 1 m. Along the lower Gulf Coast (Tampa to Naples) waves are generally 0.5 m or less. Kurotsis values for the east coast range from 3.0 (perfectly Gaussian) to 3.5, while along the lower Gulf K is greater than 3.5.

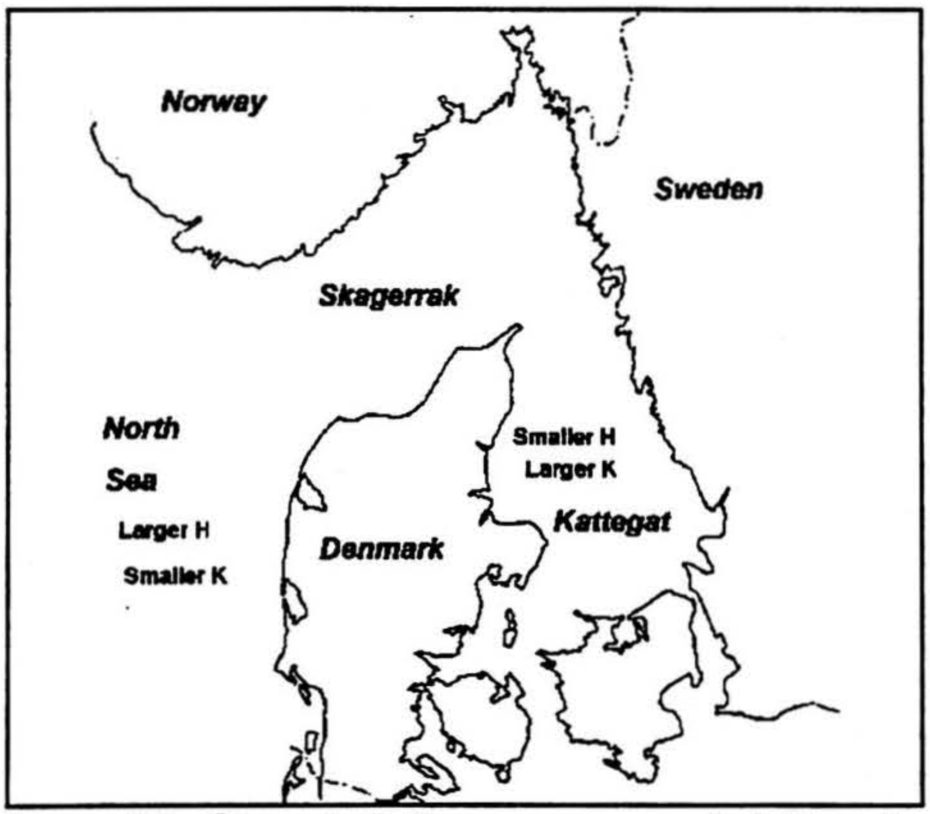


Figure 26. Characteristic average wave height and kurtosis conditions for opposing coasts of Denmark.

Case 2. Denmark. The fetch is narrow for the Kattegat (Figure 26) separating Denmark and Sweden and characteristic wave heights are smaller than for the North Sea where the fetch is only slightly sheltered by the British Isles but not from northwest winds. The result is that Danish east coast sediments have a

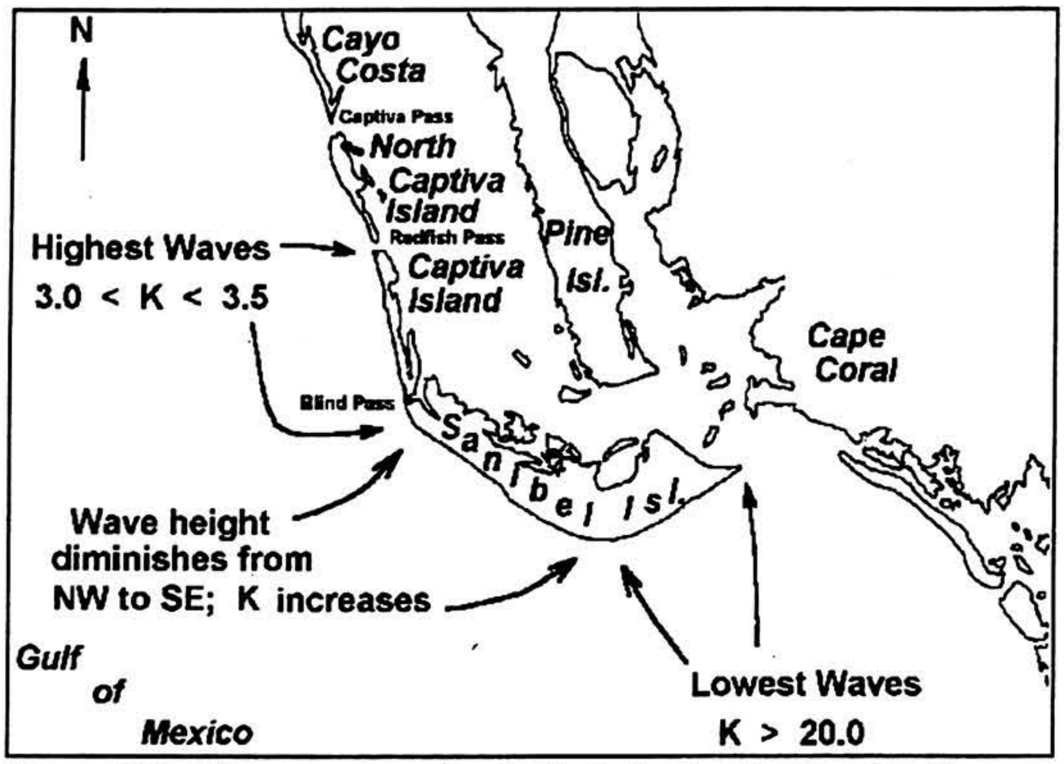


Figure 27. Wave energy - kurtosis behavior for the Captiva-Sanibel Island coastal reach.

larger characteristic kurtosis value (lower wave energy) than the Danish west coast beach sediments (higher wave energy).

Case 3. Captiva and Sanibel Islands, Lower Gulf Coast of Florida. Cases 1 and 2 represent coastal reaches of regional extent. Let us look at some specific cases representing more localized coastal reaches.

There are no quantified wave height data for the Captiva-Sanibel Island coastal reach. Wave refraction analyses, however, show that wave heights along the northern portion of the reach are largest. As the coastal curvature trends to the southeast and east, sheltering occurs and characteristic wave heights significanlty diminish (Figure 27). Corresponding response of the kurtosis is also significant (see Tanner (1992a, fig. 1) for quantitative details of the kurtosis data). It is to be noted that beach sediments along Sanibel and Captiva can be comprised totally of carbonate material. Care was taken, therefore, that the samples for this study were comprised of as much siliciclastic sand as was possible.

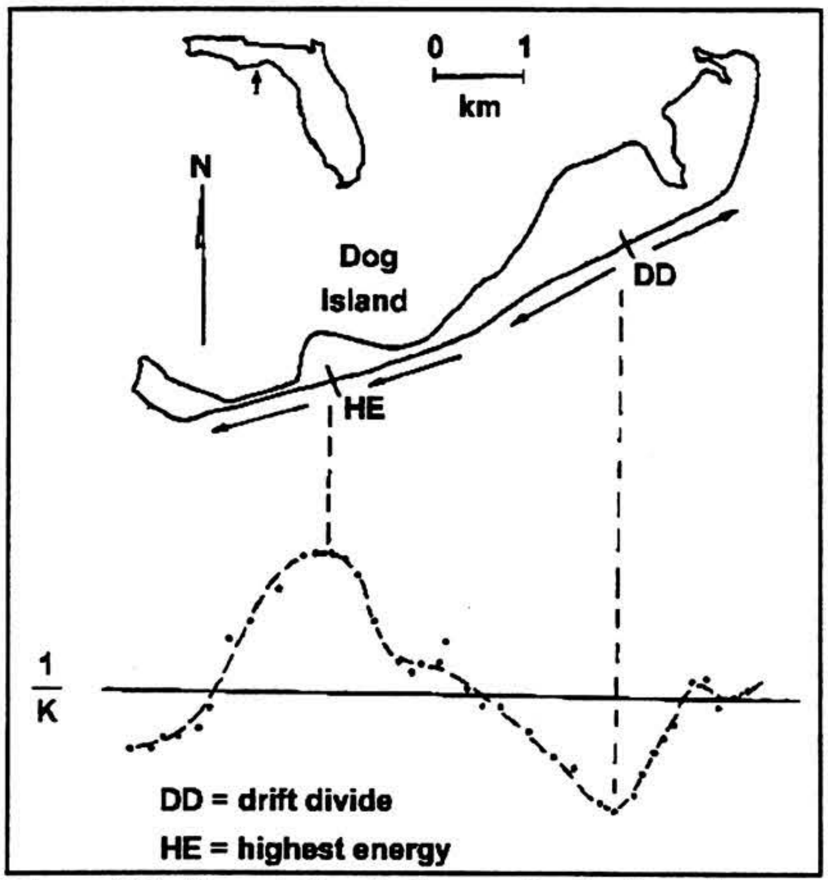


Figure 28. Correlation between kurtosis and wave energy in terms of longshore transport energies for Dog Island, Florida. (After Tanner, 1990b).

Case 4. Dog Island, eastern Panhandle Coast of Northwest Florida. This example is for a reach located immediately adjacent to the classical zero energy Big Bend coast of Florida (Tanner, 1960a), located at the eastern end of the northwestern Panhandle Gulf Coast of Florida. Wave heights and energy are low. Results should, therefore, be quite sensitive regarding the interaction of wave forces and divergence or "drift divide" near the eastern central portion of the island (Figure 28). A combination refraction-longshore transport analysis confirms that lowest wave energy occurs at the drift divide (point DD). Highest energy levels occur at point HE. The refraction analysis attenuates shoaling waves, while the longshore transport equations are wave height driven. Forty-four lower beach sand samples were collected and analyzed (Tanner, 1990). Once again, kurtosis values are largest for the low wave energy portion of the island, and are smallest for the higher wave energy portion of the island.

Case 5. Laguna Madre, Texas. The southern part of Laguna Madre is located near Boca Chica east of Brownsville, Texas. This part of the lagoon is separated from the Gulf of Mexico by a long, narrow, sandy peninsula. Two modern beach samples collected from the lagoon side had a kurtosis of 4.11, and 10. Adjacent and slightly older lagoon-side beach samples had kurtosis values of 4.2 or greater. Samples from beaches fronting on the Gulf of Mexico, however, had an average kurtosis of 3.39. The peninsula is a product of high-energy processes, as is indicated by the lower kurtosis.

Kurtosis versus Seasonal and Short-Term Hurricane Impacts:

While we should certainly desire more data on seasonal effects and extreme climatological impacts, there are not much data yet amassed. Even so, the following should pique one's interest!

Rizk (1985) studied beach sediments along Alligator Spit, located to the south of Tallahassee, FL and some few kilometers to the northeast of Dog Island. Again, overall wave energy is not high for the reach. In addition, the beaches of Alligator Spit had not experienced the effects of hurricane impact in 9 years. Rizk found a correlation between kurtosis and wave energy levels, the latter being higher during the spring than the summer. Hence, kurtosis can distinguish seasonal effects. In addition, Figure 29 indicates that the standard deviation of the suite of samples, σ_K, also correlates with extreme event energy conditions, being smaller in value during higher energy conditions, ..., larger during lower energy conditions.

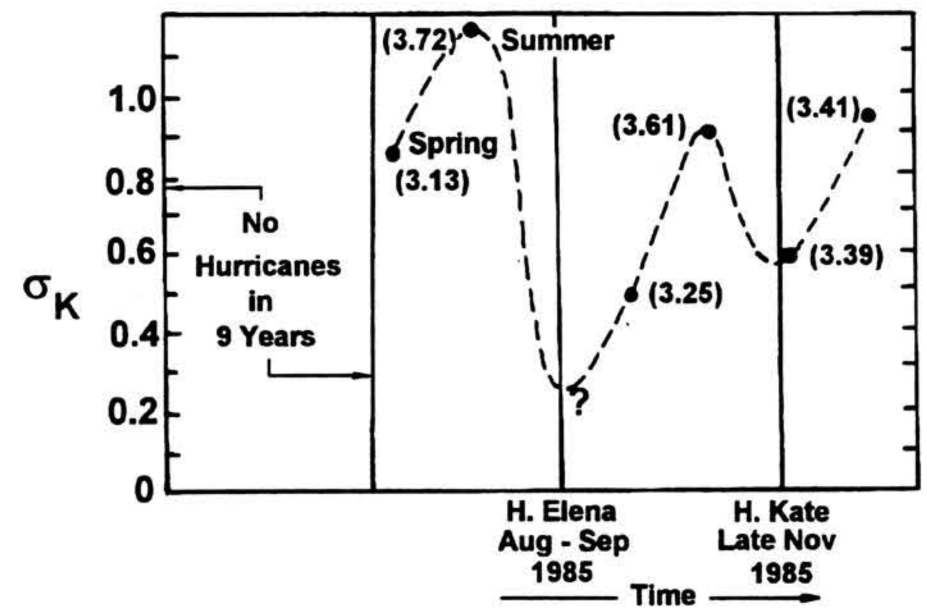


Figure 29. Kurtosis data versus energy levels for seasonal effects and hurricane impacts for Alligator Spit, Florida. Kurtosis values are in parentheses, σ_K is the standard deviation of the kurtosis values of the sample suite kurtosis. (After Tanner, 1992a).

Two successive hurricanes impacted the area in 1985 (see Figure 29), and ensuing sedimentologic response was monitored by Rizk and Demirpolat (1986). During high energy sedimentologic response was monitored by Rizk and Demirpolat (1986). During high energy conditions of Hurricane Elena kurtosis values were low compared to conditions weeks after the event. Note that shore-incident storms or hurricanes, not only produce exceptionally high waves, but also storm tides (which being a super-elevated water surface) allow for even higher waves (since waves are depth limited) closer to shore. Kurtosis values immediately after impact of Hurricane Kate and several weeks later are not different. Why this is so, is not clearly understood. Even so, standard deviations of the sample suites, σ_K, do show a correlation. Hence, σ_K is an additional tool that can provide valuable information.

Kurtosis and Long-Term Sea Level Changes:

Beach ridges are formed by small couplets of mean sea level rise and fall (10 to 30 cm). In order to appreciate how beach ridge formation occurs, there must be some understanding of coastal, beach, nearshore, and offshore dynamics. First, in the topographic sense, slopes for nearshore and offshore profiles are very gentle. Relief of any proportion at all does not occur until the shoreward portion of the nearshore, the beach, and the coast are encountered. Second, where shore-propagating waves begin to be attenuated due to drag effects with the bed is a function of the wave length. The deep water wave length, L_o, in meters is given by $L_o = 1.56 T^2$ where T is the wave period. The water depth where drag effects begin to occur is approximately given by $L_o /2$. Third, farther nearshore, waves are depth-limited. That is, waves will distort and break according to $d_b = 1.28 H_b$ where d_b is the water depth at breaking and H_b is the height of the breaking wave. Finally, where breaking is represented by final shore-breaking (i.e., the breaking waves cannot reform and again rebreak) swash runup mechanics are important in inducing final sedimentologic transport.

Let us look at the case where there is a drop of several meters in sea level as illustrated in Figure 30a. For the pre-sea level drop case let us suppose that waves begin to experience bed drag at point A. There is, then, the distance a-A over which the waves will attenuate to eventually shore-break with a breaker height of H_{ba}. However, when sea level drops these same deep water waves will begin to experience bed drag at point B which continues for the distance b-B, a distance that is much greater than distance a-A. That is, the longer the distance, the greater the attenuation of the wave height. Hence, where shore-breaking, H_{bb}, occurs for the sea level drop scenario, H_{bb} will be <u>smaller</u> than H_{ba}. Hence, breaker energy levels will be <u>less</u>, at least initially (i.e., a readjustment period of approximately 2 or 3 centuries might be appropriate for the Gulf of Mexico), when sea level drops.

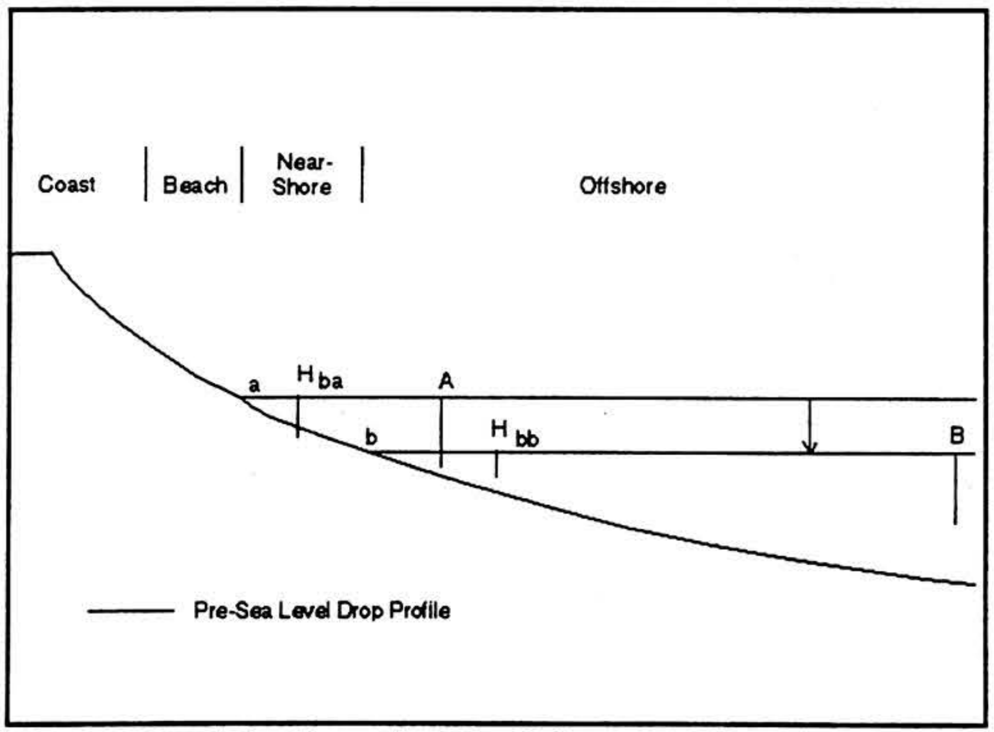


Figure 30a. The littoral and offshore profile and effect of sea level drop on wave energy levels.

Let us inspect the case for sea level rise, illustrated in Figure 30b. Just the opposite occurs for sea level rise, compared to the sea level drop scenario. The distance a-A for the pre-rise sea level is longer than for the b-B distance following sea level rise. Moreover, shore-breaking wave heights H_{bb} will be larger than H_{ba}.

If we have learned our lessons from previous experience, it should be clear that **kurtosis values for a sea level drop should be large** and **kurtosis values for a sea level rise should be small.**

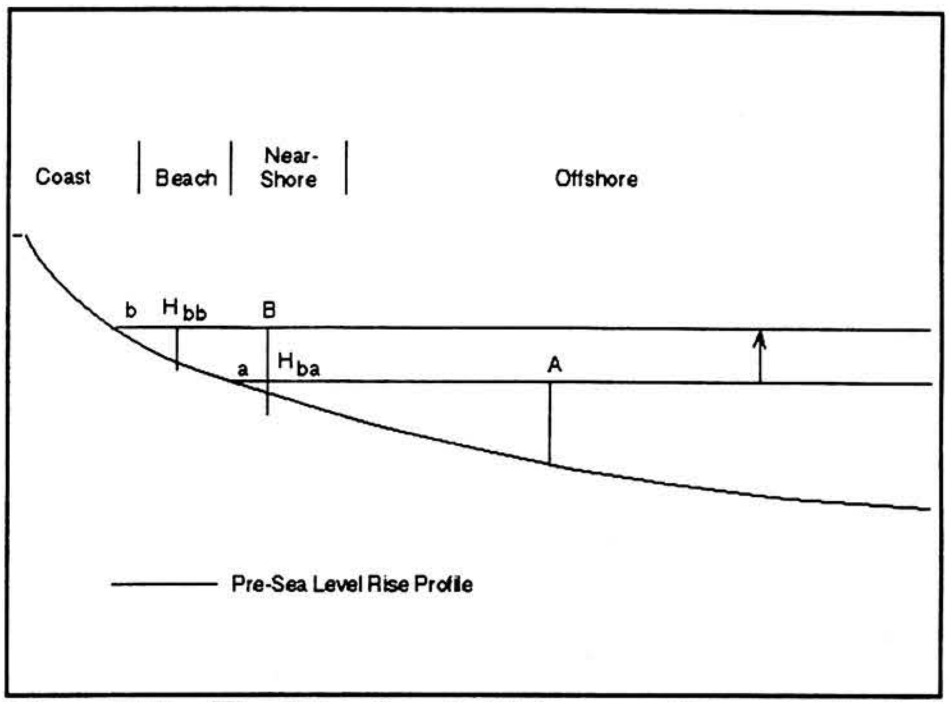


Figure 30b. The littoral and offshore profile and effect of sea level rise on wave energy levels.

St. Vincent Island, Florida, Beach Ridge Plain. St. Vincent Island, a federal wildlife refuge, is located south of the town of Apalachicola along the eastern part of the northwestern panhandle coast of Florida. It is comprised of a sequence of beach ridge sets ranging in age from set A (oldest) to set K (youngest) as illustrated in Figure 31. Sets A, B, and D stand low. Three dates are available for the island: an archeological date of older than 3,000 - 3500 years B. P. (before present) is found on the northwest; a C^{14} date of 2110 ± 130 years B. P. near the east coast, and historical records of pond closure of approximately 200 years for the southern coast. Each beach ridge has been repetitively surveyed and sampled for granulometric analysis, by different investigators. Laminar samples for the seaward face of each ridge (one sample each) were taken at depths of from 30 to 40 cm. The different investigators did not know where the others had conducted work. Results were statistically identical for the 59 individual ridges along the profile.

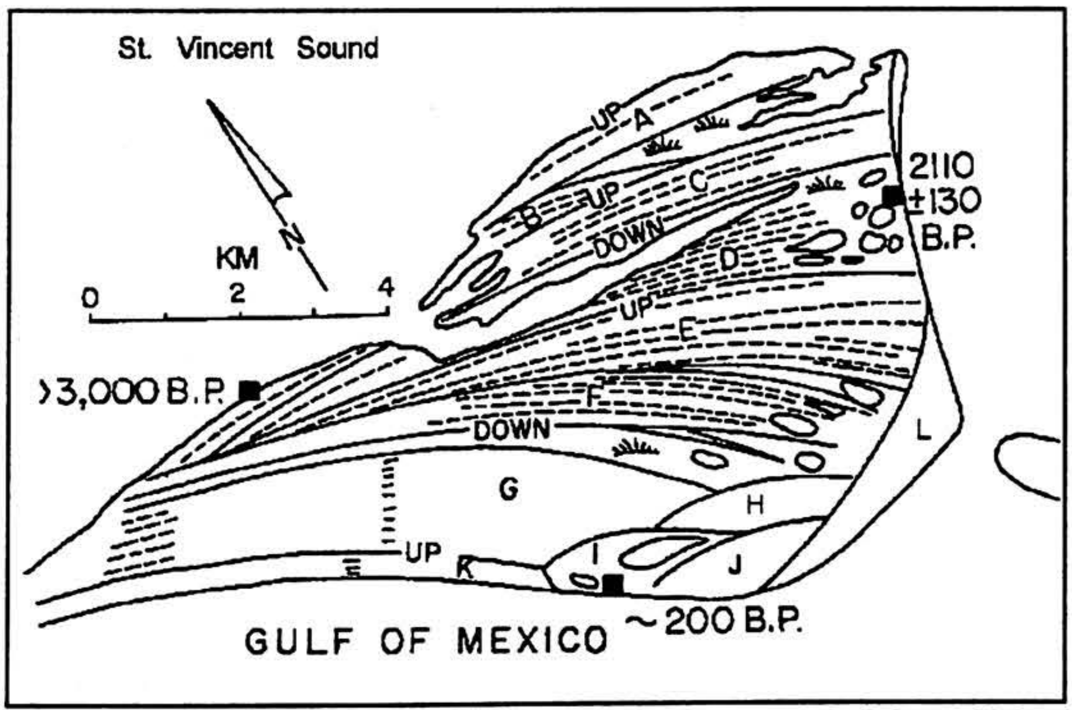


Figure 31. The St. Vincent Island beach ridge plain. (After Stapor and Tanner, 1977).

We should expect that when sea level drops,

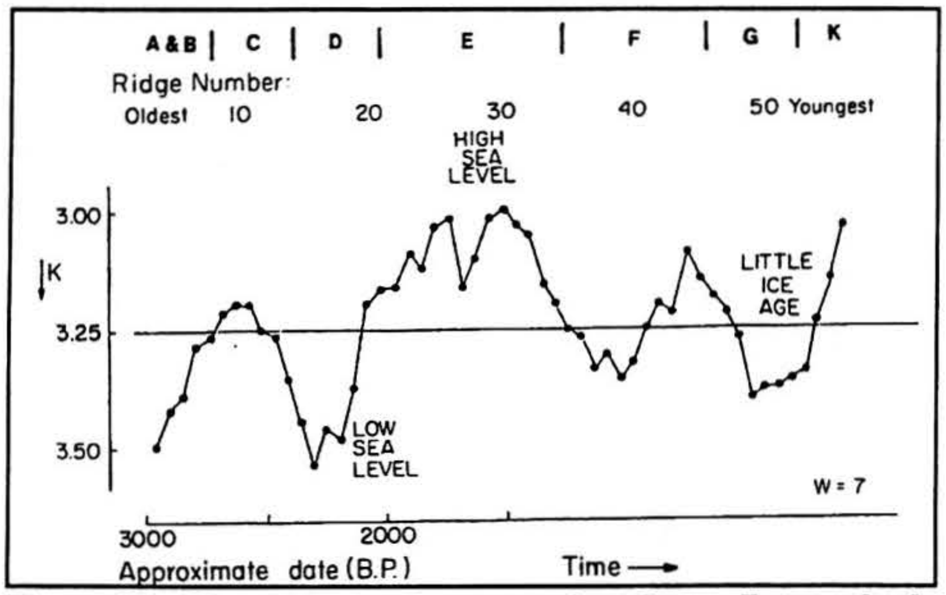


Figure 32. Plot of kurtosis versus time for sedimentologic data from the St. Vincent Island Beach Ridge Plain. Letters at the top of the figure identify location of beach ridge sets of Figure 30. (After Tanner, 1992a).

kurtosis values should increase and when sea level rises kurtosis should decrease. This is precisely what happens as illustrated by Figure 32. Time spacing between points is approximately 50 years. Note that the beach ridge sets (sets are comprised of multiple beach ridges) each represent a different sea level stand and differ from one another in topographic height by about 1 or 2 meters. Also note that the ordinate is inverted to simulate 1/K to directly correlate with hydrodynamic energy levels. Sea level changes range from 1 to 2 meters, and the plot includes 4 rises and 3 drops in sea level (see Tanner, 1992a, for additional details). There are two (2) conclusions:

1. Whether there are topographic data or not, one can (based on the kurtosis), identify when sea level rise occurred or when it fell.

2. Based on the kurtosis values, not a single value represents a storm. That is not to say that there are not laminae where K would represent storm activity, just that none were found. Certainly, there were storms in its 3,000-year history ... none have as yet been isolated.

St. Joseph Peninsula Storm Ridge. However, Felix Rizk in work along St. Joseph Peninsula, not too far to the west of St. Vincent Island, found a storm produced ridge, amongst a beach ridge set, which is called the Storm Ridge. It's relief is about 4 meters, 20 to 25 m wide at the base. There are results for some 40 sand samples from the ridge, which is composed of uniform bedding sloping at from 18 to 20 degrees downward in the seaward direction. Granulometry indicates storm depositional conditions. This is the **ONLY** storm ridge (not a lamina or a berm, but a complete ridge) in a beach ridge set that W. F. Tanner has found along the coastal northeastern Gulf of Mexico. What are the chances of a storm ridge being preserved here? Undoubtably it is much less than 1%, and one might venture it is on the order of 0.01%.

Beach Ridge Formation - Fair-Weather or Storm Deposits?:

Of all the hundreds of beach ridges investigated, only one isolated beach ridge formed by a storm (preceding paragraph) has been identified by W. F. Tanner. However, in the popular textbook literature there is espoused the notion that each modern beach ridge we see today has been produced by a single storm event. In these same texts, however, it is without exception, noted that storms erode beaches and coasts. These are diametrically opposed outcomes. Beach ridges are, with rare exceptions, fair-weather swash deposits. They are formed by small sea level rise followed by a small sea level drop occurring over a period of from 10 to 50 or so years. Runup from final shore-breaking waves plays an important role, where higher runup (larger breakers) forms the ridges and small runup (smaller breakers) forms the swales.

Texas Barrier Island Study - Conversation with W. Armstrong Price. A number of years ago, W. A. Price had a summer contract to survey by plane table barrier islands and their lagoonal beaches between Brownsville and Corpus Christi, Texas. Two or so months into their work, Price and his survey crew noticed (having not been in that particular area for some time) a beach ridge on the lagoon side of a portion of the locale. This discovery brought a halt to field work while they re-checked their maps in order to determine if they had originally missed the feature. Confident in their work, it was decided the beach ridge was a new feature. Based on prevailing literature that each beach ridge is the product of a single storm, Price checked the records and found no such occurrence. How the beach ridge formed in a month or two is not known. However, it was not storm-produced.

Transpo-Depositional Energy Levels and the Kurtosis; and an Explanation:

From the preceding examples we can draw some general conclusions. In general, kurtosis and transpo-depositional energy levels can be related. A diagrammatic representation is suggested by Figure 33, for which the energy, E, is related to the kurtosis, K, according to:

$$K = fn\,[E^{-1}]$$

where for waves $E \propto H^2$, where H is the wave height.

Tanner and Campbell (1986) found K values ranging from 3.7 to 13 for beaches of some Florida lakes, which represent a combination of low wave energy and settling mechanics.

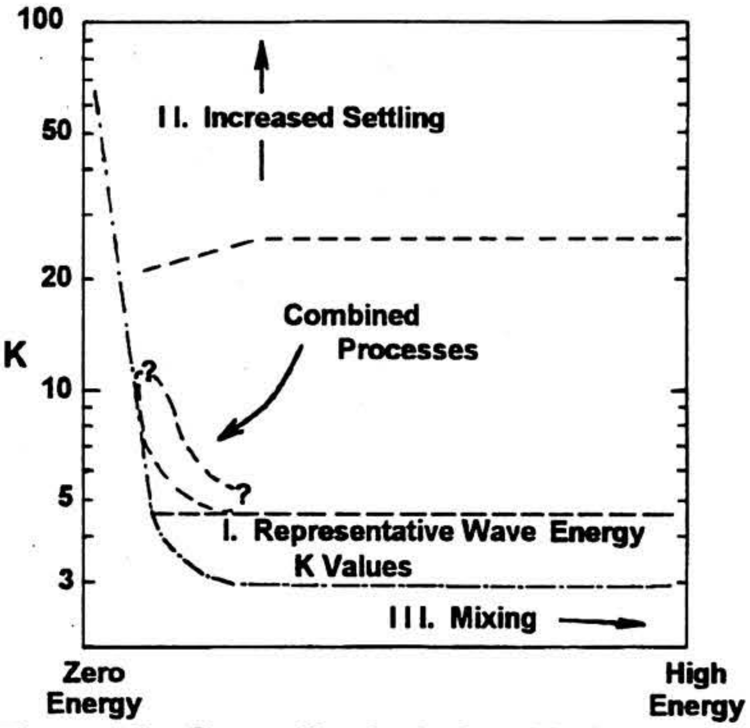


Figure 33. Generalized relationship between energy levels and kurtosis.

A consistent algebraic expression relating K and energy levels, in particular, wave energy for sand-sized and finer sediments, has not been discovered.

What, then, is the explanation for the inverse relationship between kurtosis and energy levels? Let us use the littoral zone as an example, one characteristically experiencing, say, low to moderate wave energy levels. Suppose that normal wave conditions are operating wherein shore-propagating waves break once at the shoreline. It is well known that sediments just shoreward of the breaker position (e.g., plunge point and foreshore slope) are the coarsest sediments found along the beach and offshore profile. This occurs because finer sediments are sorted out, and transported alongshore and offshore. The result is that the sedimentologic distribution is compressed, leading to a peaked or leptokurtic kurtosis ($K > 3.0$). Suppose that a storm makes impact. Now, energy conditions are greatly increased due to both an increase in the water level (storm tide) and larger incident waves. In fact, because of fully aroused seas, waves are breaking across the entire littoral zone which is significantly wider than under normal conditions, affecting not only the nearshore, but also the beach. The result is a significantly wide high energy expenditure zone where sediment mixing occurs. That is, more sediment is added to the tails of the distribution, resulting in a reduction of the kurtosis relative to normal conditions, and reaching a value of $K \approx 3.0$.

Importance of Variability of Moment Measures in the Sample Suite

Refer to the Friedman-Sanders plot (Figure 16). The apparent reason of this figure is to convince the reader that such comparison does not work as an analytical tool. Let us assume their samples were correctly taken, etc. In addition, let us look, for the moment, at the hydrodynamic differences between beaches and rivers.

Uprush and backwash on beaches are characterized by a thin layer or "sheet" of water 1 to 5 cm thick. Hydrodynamically, this condition should be represented by very small Reynolds numbers ($\mathbb{R}$) and very large Froude numbers ($\mathbb{F}$). River channels, on the other hand, with much greater depths and unidirectional flow conditions, should have large $\mathbb{R}$'s and very small $\mathbb{F}$'s. These differences are great enough that the beach and river points of Figure 16 should not overlap. Why the overlap? There is a basic principal that requires observance: ***the hydrodynamic information we obtain from granulometry is the result of the variability from sample-to-sample within the sample suite***. If the same level of energy of a force element (e.g., waves) is the same day-after-day-after-day, the variability between sand samples representing daily samples should be very small. However, this is almost never the case. Rather, there is not only turbulence but **multi-story** turbulence; that is, turbulence on quite different scales due to different energy levels and features. Hence, it is desirable that there should be some degree of variablity between parameters such as the mean or kurtosis, etc., for samples comprising the sample suite. Therefore, Friedman and Sanders should have used averages of sample suite parameters.

Application of Suite Statistics to Stratigraphy and Sea-Level Changes

Refer to Appendix VIII entitled ***Application of Suite Statistics to Stratigraphy and Sea-Level Changes*** (W. F. Tanner, 1991, Chapter 20, [In] ***Principals, Methods, and Application of Particle Size Analysis***. Cambridge University Press). Discussion of the rationale for Chapter 20 (i.e., Appendix VIII, this work) is given by Chapter 16 (i.e., Appendix VII, this work).

Cape San Blas, Florida [Appendix VIII, p. 116, 3rd paragraph].

The beach sands of Cape San Blas provide simple and straightforward granulometric interpretations (see the reference). Let us look at a more complicated case.

Médano Creek, Colorado [Appendix VIII, p. 116, last paragraph].

This locality was selected for study to avoid the charge of looking only at simple or easy examples. It is not an easy example.

Médano, pronounced MED (as in ED) - ăNO, is Spanish for "sandy place". Médano Creek, located in central Colorado, flows through Great Sand Dunes National Monument in a southerly direction along the eastern side of the sand dunes (Figure 34). The dunes have a relief of some hundreds of feet. To the east of the creek lies an area of crystalline rocks. The creek bed, which is very flat because it is composed of quartz sand with no binding fines (i.e., silts or clays), is about 20 meters wide with water depths of only about 2 cm. Prevailing winds from west to east provide one source of sediments to the creek. The other is the creek itself.

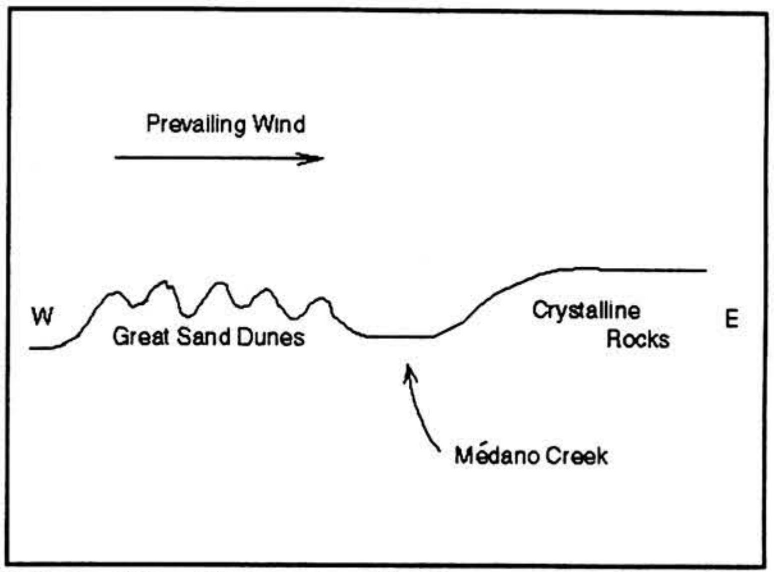


Figure 34. Conceptualized cross-section of the Great Sand Dunes and Médano Creek (drawing not to scale).

Sand samples (23, which is a large number of samples, rarely are this many needed) from the Great Sand Dunes, using plotting techniques of Figure 19 through 23, confirm eolian transport and deposition. Note also, using the diagrammatic probability plot (Figure 22), only 1/4 to 1/2 of the plots need to show the eolian hump to confirm eolian processes. The creek samples show a faint but sharply developed fluvial coarse tail. If the creek sands were lithified and sampled in section, the environmental intrepretation would probably be dune, but some minor fluvial influence should be evident... remember, this is a very shallow creek not a river of consequential dimensions. Hence, we should be looking for subtleties. One might consider these to be coastal dunes. However, homogeneity of parameters for the suite of samples is greater than one would find in coastal environments, and they should be recognized as non-coastal eolian sediments. Greater homogeniety for eolian transport should occur because of the greater mass density differential between air and quartz, than it is between water and quartz. Even so, swash zone sediments do also show remarkable homogeneity due to the number of uprush and backwash events that occur.

Note also the Tail-of-Fines Diagram (Appendix VIII, p. 117, figure 20.1) and The Variablity Diagram (Appendix VIII, p. 117, figure 20.2). Do these plotting techniqes (i.e., Figures 19 through 23) plot with 100% assurance? Note that the river, R, suite results misplot on figure 20.2 (Appendix VIII, p. 117). So, they do not always plot with total success. Individual plotting tools appear to have maximum success rates of from 80% to 90%. However, taken all together, the diagrams have a success rate of from 90 to 95%.

The Suite Skewness Versus Suite Kurtosis Plot (Appendix VIII, p. 120, figure 20.3) does not allow one to distinguish fluvial from beach sands, but does allow one to distinguish between eolian and hydrodynamic influences.

St. Vincent Island Beach Ridge Plain

Figure 20.4 of Appendix VIII, page 121, is an example from computer program LINEAR for sediment samples from beach ridges 1 through 37 (the older ridges) for St. Vincent Island. The plot comprised of $ represents a 3-point floating average for 1/K. The program identifies, based on a mean/kurtosis quotient of 0.68, where sea level should be low by the "LOW?" designation which can be confirmed from topographic data for beach ridge set elevations. Other parameters which also correlate with changes of sea level stands are the quotients mean/kurtosis and standard deviation/kurtosis, and differences of the standard deviations. Beach ridge set sedimentologic means and set means of the standard deviation also provide information. These are discussed on page 120, 2nd column of Appendix VIII.

The Relative Dispersion Plot

The Sediment Analysis Triangle is again discussed on page 121 of Appendix VIII. An additional interpretative aid is provided by the Relative Dispersion Plot (Appendix VIII, p. 122, figure 20.6) shown here as Figure 35. The relative dispersion, R. D. (also known variously as the coefficient of variation), is given by:

$$R.D. = \frac{Standard\ Deviation}{Mean} = \frac{\sigma_\phi}{M_\phi} = \frac{\sigma_\phi}{\mu_\phi}$$

If the standard deviation is large because the mean is large, one does not want to interpret the result in terms of the scatter. The relative dispersion eliminates this effect. Two parameters are calculated for use in the Relative Dispersion Plot. The relative dispersion of the means, $\mu^\star$, is given by:

$$\mu^\star = \frac{\sigma_\mu}{\mu_\mu}$$

in which σ_μ is the standard deviation of the means of the suite samples, and μ_μ is the mean of sample averages comprising the suite. The relative dispersion of the standard deviations, $\sigma^\star$, is evaluated by:

$$\sigma^\star = \frac{\sigma_\sigma}{\mu_\sigma}$$

where σ_σ is the average standard deviation of the sample standard deviations comprising the suite, and μ_σ is the mean value of the

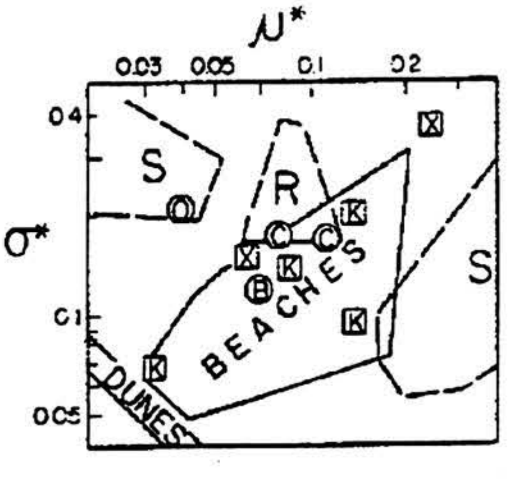


Figure 20.6. Relative dispersions of means and standard deviations, showing settling (S), river (R), beach, and dune areas. There is a small overlap at two places. See Figure 20.1 for key.

Figure 35. The Relative Dispersion Plot. (From Tanner, 1991b).

standard deviations of the suite samples.

Note from Figure 35 that there are some small regions that overlap. Even so, the Relative Dispersion Plot provides an additional and useful analytical tool. Again, these plotting tools ... Figures 19 through 23 and Figure 35 and computer tools such as GRAN-7 ... when the results are tallied, have never resulted in a tie between transpo-depositional agencies. A predominant mechanism has always surfaced to identify the last mode of the depositional environment. Copies of these working plotting tools (and a few others which have merit) are provided in Appendix IX.

The SUITES Progam

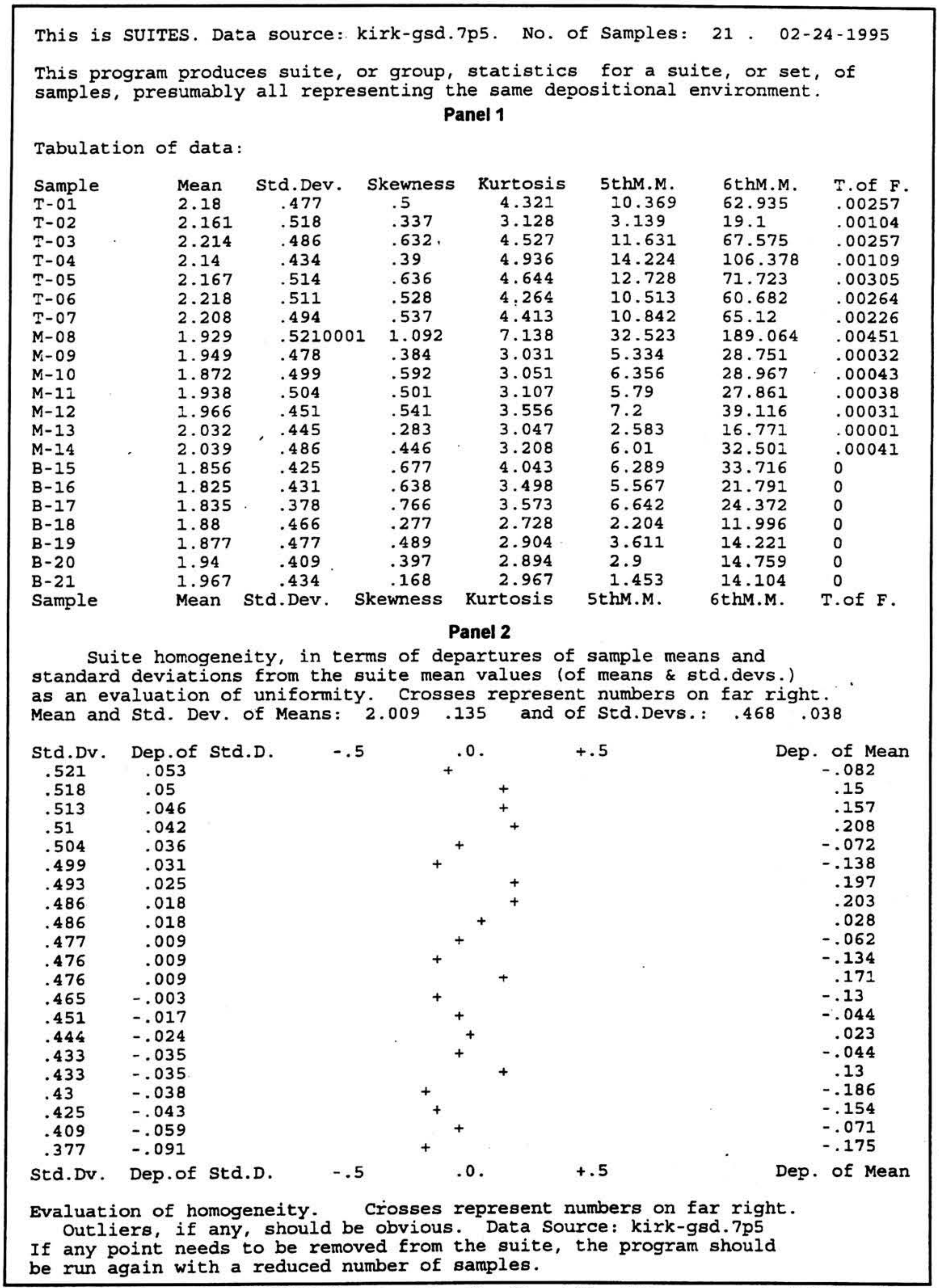
The SUITES computer program, written by W. F. Tanner, provides the means for computing suites statistics and for assessing the results. The program requires stored output generated by the GRAN-7 computer program. Following are examples.

Example 1. Great Sand Dunes, Colorado.

Figure 36 represents SUITES output for the Great Sand Dunes just to the west of Médano Creek, Colorado. There are 21 samples. Notice from panel 1 that the samples are so "clean" that there is no tail-of-fines. Inspect the 2nd panel entitled "suite homogeneity". Plotted values are much less than ± 0.5 σ. This is marvelously good homogeneity. Good homogeneity would occur near ± 0.5 σ. Even for excellent or good homogeneity outliers are possible. Consistently poor homogeneity, or heterogeneity, e.g., from high energy rivers, glacial-fluvial deposits, etc.), would exceed ± 0.5 σ. In panel 3, the vertical columns contain the basic parameters that we are summarizing in the SUITES program. The horizontal lines are suite means, standard deviations, kurtosis, etc. of the basic data. The last (4th) panel provides an environmental analysis. It states the procedures used and assesses 6 commonly encountered sedimentologic depositional environments, i.e., dune, mature beach (MB), river (Riv), settling from relatively still water (Sett), tidal flats (TFlat), and glacio-fluvial (GLF). A capital X signifies assured environmental identification of the transpo-depositional environment, a lower case x indicates less assured identification. The highly diagnostic eolian hump is identified from the probability plot and interactively noted in the data entry portion of the SUITES program. The overwhelming evidence identifies that the deposit is, indeed, eolian.

Example 2. Storm Ridge, St. Joseph Peninsula, Florida.

Felix Rizk found the St. Joseph Peninsula Storm Ridge locality. W. F. Tanner sampled the deposit. This storm deposited ridge described previously (p. 34) is located along the central portion of St. Joseph Peninsula (see Figure 41 for an approximate location). Suite results are given by Figure 37. Rizk took his samples in a vertical direction (14 or 15 samples), which meant that they represented the difference between the upper and lower portions of the swash resulting from final shore-breaking storm wave activity. W. F. Tanner, however, re-sampled (21 samples) the ridge in a horizontal direction to look at the middle or central portion of swash/runup force element activity. The results provided more continuity. Panel 2 indicates very good homogeneity, internal to which there is variability and, therefore, a good suite of samples. [NOTE: the computer file extension .5P5 indicates that the original data source generated from GRAN-7 contained 5 parameters with the pan fraction



```
This is SUITES. Data source: kirk-gsd.7p5.  No. of Samples:  21 .  02-24-1995

This program produces suite, or group, statistics  for a suite, or set, of
samples, presumably all representing the same depositional environment.
```

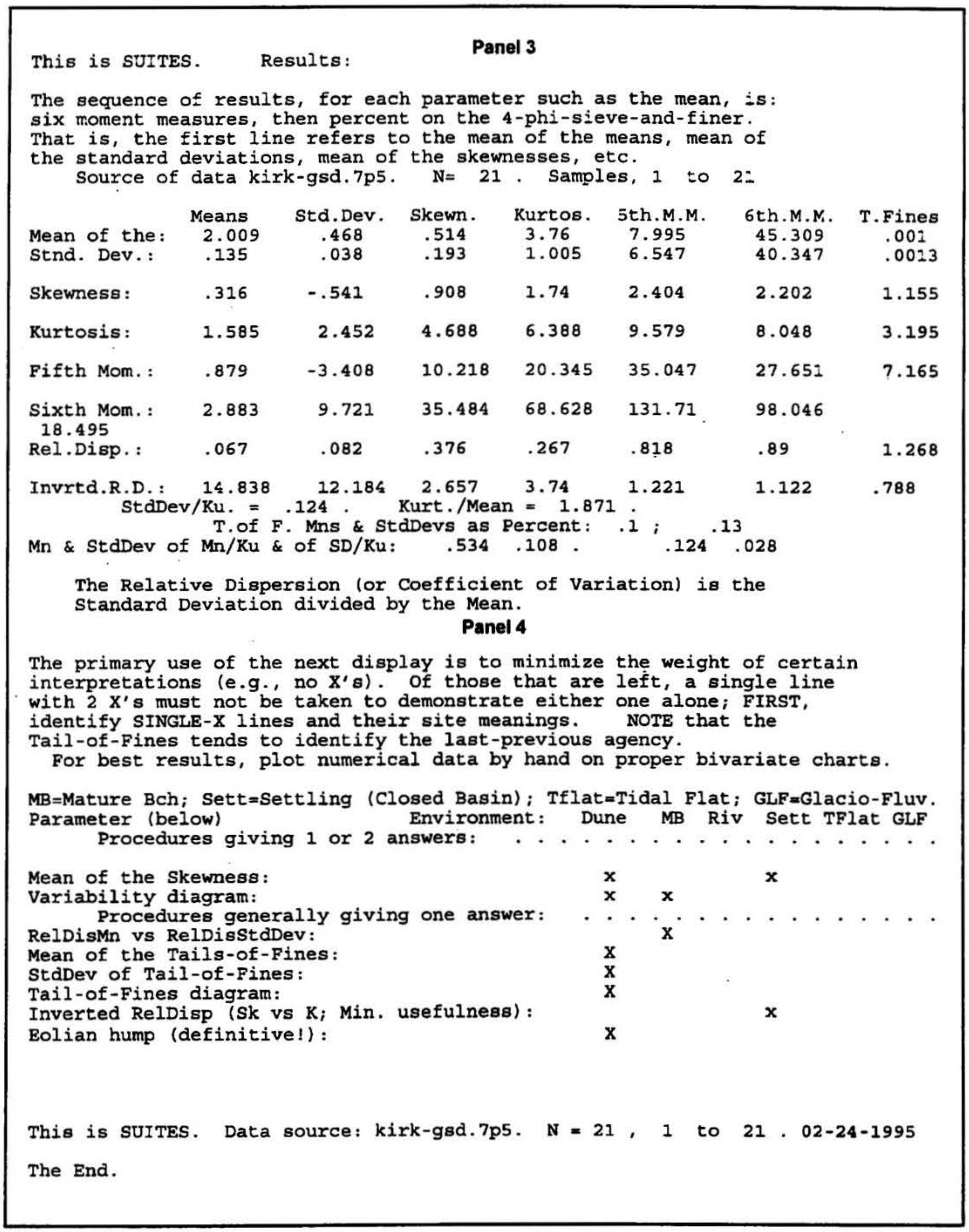
Panel 1

```
Tabulation of data:

Sample       Mean   Std.Dev.  Skewness  Kurtosis   5thM.M.    6thM.M.   T.of F.
T-01         2.18     .477      .5        4.321    10.369     62.935    .00257
T-02         2.161    .518      .337      3.128    3.139      19.1      .00104
T-03         2.214    .486      .632      4.527    11.631     67.575    .00257
T-04         2.14     .434      .39       4.936    14.224     106.378   .00109
T-05         2.167    .514      .636      4.644    12.728     71.723    .00305
T-06         2.218    .511      .528      4.264    10.513     60.682    .00264
T-07         2.208    .494      .537      4.413    10.842     65.12     .00226
M-08         1.929    .5210001 1.092      7.138    32.523     189.064   .00451
M-09         1.949    .478      .384      3.031    5.334      28.751    .00032
M-10         1.872    .499      .592      3.051    6.356      28.967    .00043
M-11         1.938    .504      .501      3.107    5.79       27.861    .00038
M-12         1.966    .451      .541      3.556    7.2        39.116    .00031
M-13         2.032    .445      .283      3.047    2.583      16.771    .00001
M-14         2.039    .486      .446      3.208    6.01       32.501    .00041
B-15         1.856    .425      .677      4.043    6.289      33.716    0
B-16         1.825    .431      .638      3.498    5.567      21.791    0
B-17         1.835    .378      .766      3.573    6.642      24.372    0
B-18         1.88     .466      .277      2.728    2.204      11.996    0
B-19         1.877    .477      .489      2.904    3.611      14.221    0
B-20         1.94     .409      .397      2.894    2.9        14.759    0
B-21         1.967    .434      .168      2.967    1.453      14.104    0
Sample       Mean  Std.Dev.  Skewness  Kurtosis   5thM.M.    6thM.M.   T.of F.
```

Panel 2

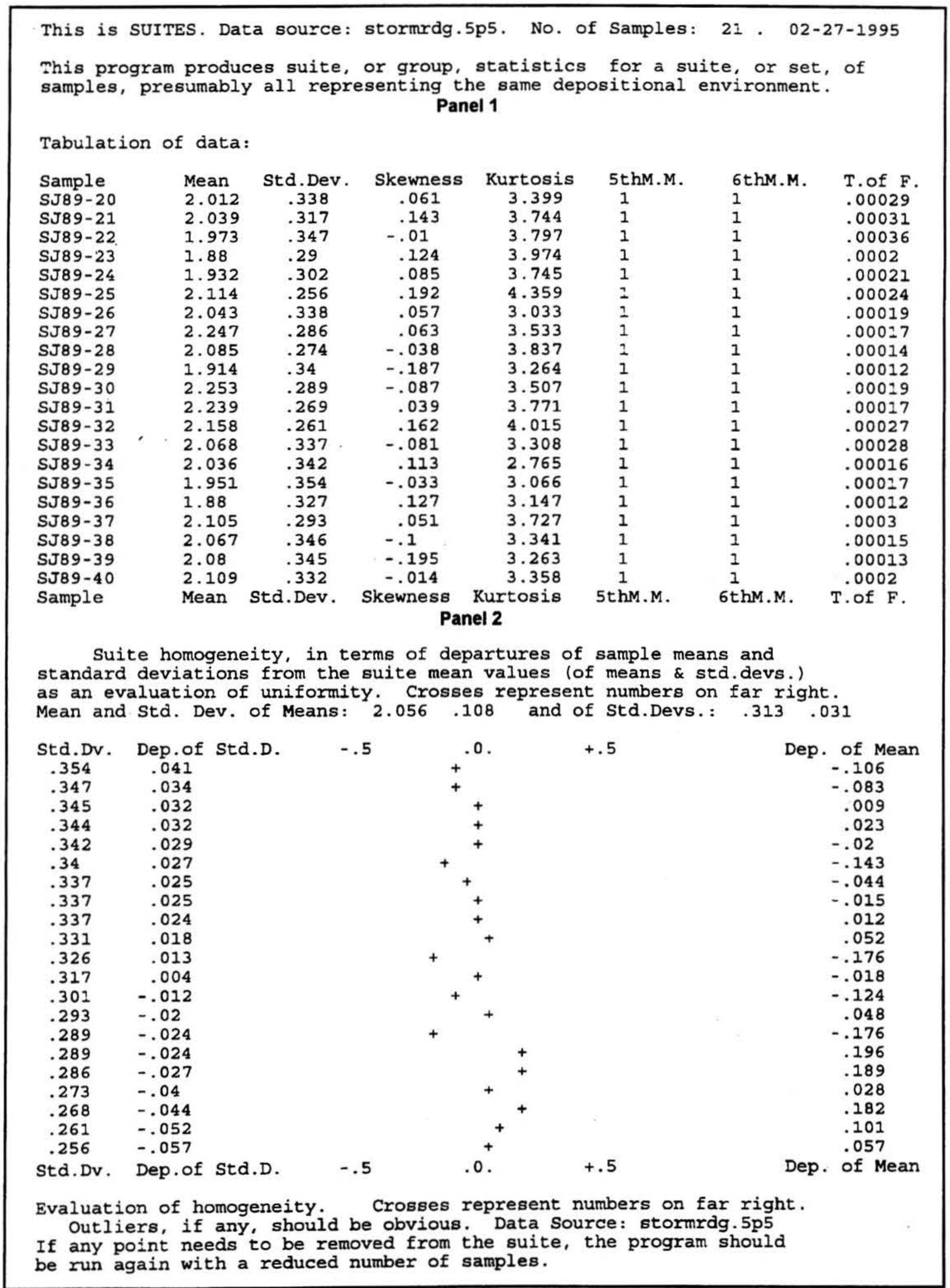
```
     Suite homogeneity, in terms of departures of sample means and
standard deviations from the suite mean values (of means & std.devs.)
as an evaluation of uniformity.  Crosses represent numbers on far right.
Mean and Std. Dev. of Means:  2.009  .135   and of Std.Devs.:  .468  .038

Std.Dv.  Dep.of Std.D.     -.5        .0.       +.5                Dep. of Mean
 .521     .053                       +                                -.082
 .518     .05                             +                             .15
 .513     .046                            +                            .157
 .51      .042                             +                           .208
 .504     .036                        +                               -.072
 .499     .031                      +                                 -.138
 .493     .025                             +                           .197
 .486     .018                             +                           .203
 .486     .018                          +                              .028
 .477     .009                        +                               -.062
 .476     .009                      +                                 -.134
 .476     .009                            +                            .171
 .465    -.003                      +                                  -.13
 .451    -.017                        +                               -.044
 .444    -.024                         +                               .023
 .433    -.035                        +                               -.044
 .433    -.035                            +                             .13
 .43     -.038                     +                                  -.186
 .425    -.043                      +                                 -.154
 .409    -.059                        +                               -.071
 .377    -.091                     +                                  -.175
Std.Dv.  Dep.of Std.D.     -.5        .0.       +.5                Dep. of Mean

Evaluation of homogeneity.    Crosses represent numbers on far right.
   Outliers, if any, should be obvious.  Data Source: kirk-gsd.7p5
If any point needs to be removed from the suite, the program should
be run again with a reduced number of samples.
```

Figure 36. Example of SUITES output for the Great Sand Dunes, central Colorado.



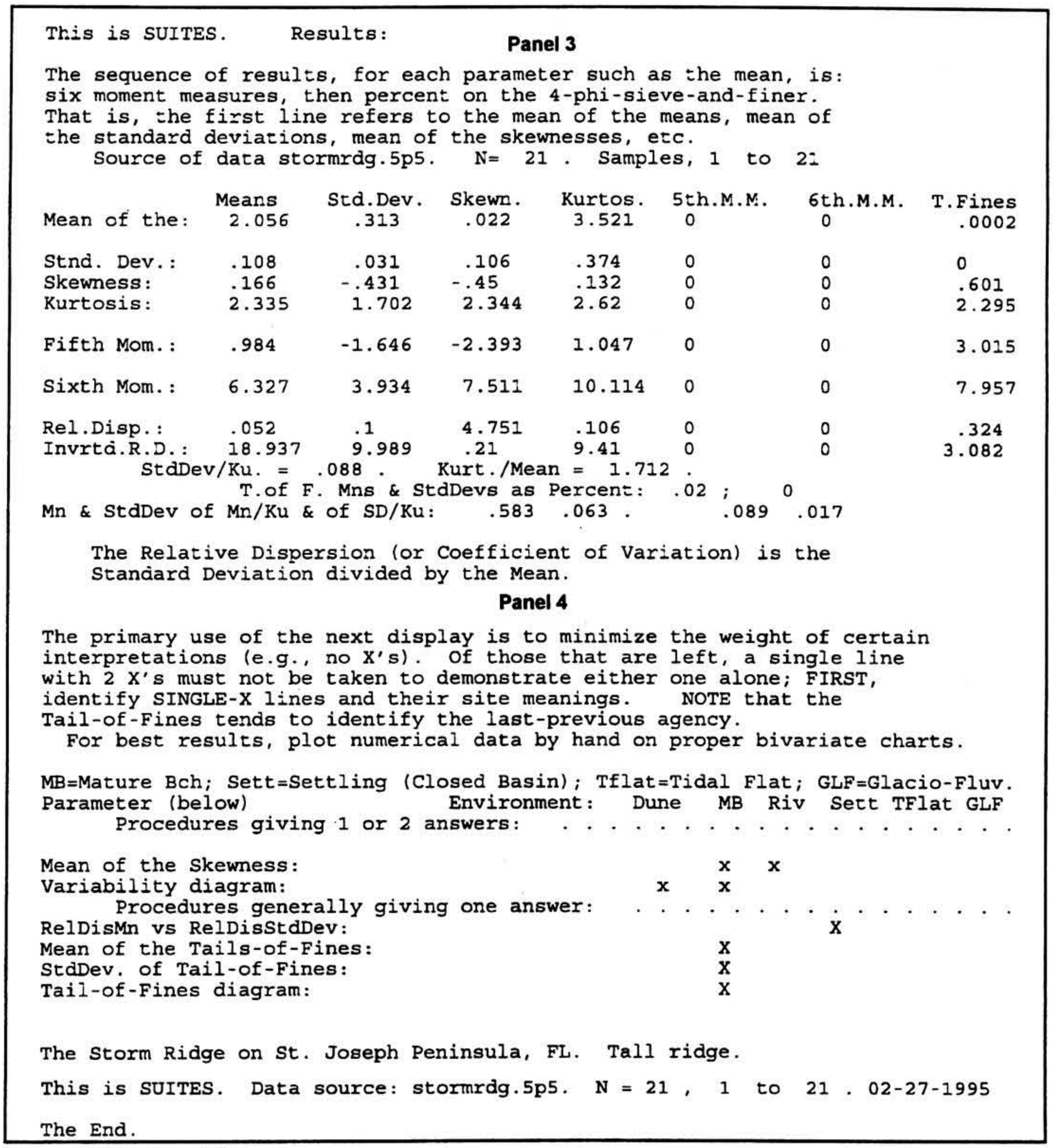
```
                                  Panel 3
This is SUITES.      Results:

The sequence of results, for each parameter such as the mean, is:
six moment measures, then percent on the 4-phi-sieve-and-finer.
That is, the first line refers to the mean of the means, mean of
the standard deviations, mean of the skewnesses, etc.
    Source of data kirk-gsd.7p5.    N=  21 .  Samples, 1  to  21

                Means     Std.Dev.  Skewn.    Kurtos.  5th.M.M.    6th.M.M.  T.Fines
Mean of the:   2.009      .468      .514     3.76     7.995       45.309     .001
Stnd. Dev.:    .135       .038      .193     1.005    6.547       40.347     .0013

Skewness:      .316      -.541      .908     1.74     2.404       2.202      1.155

Kurtosis:      1.585      2.452     4.688    6.388    9.579       8.048      3.195

Fifth Mom.:    .879      -3.408     10.218   20.345   35.047      27.651     7.165

Sixth Mom.:    2.883      9.721     35.484   68.628   131.71      98.046
 18.495
Rel.Disp.:     .067       .082      .376     .267     .818        .89        1.268

Invrtd.R.D.:   14.838    12.184     2.657    3.74     1.221       1.122      .788
        StdDev/Ku. =  .124 .    Kurt./Mean =  1.871 .
                T.of F. Mns & StdDevs as Percent:  .1 ;    .13
Mn & StdDev of Mn/Ku & of SD/Ku:     .534  .108 .        .124  .028

    The Relative Dispersion (or Coefficient of Variation) is the
    Standard Deviation divided by the Mean.
                                  Panel 4
The primary use of the next display is to minimize the weight of certain
interpretations (e.g., no X's).  Of those that are left, a single line
with 2 X's must not be taken to demonstrate either one alone; FIRST,
identify SINGLE-X lines and their site meanings.    NOTE that the
Tail-of-Fines tends to identify the last-previous agency.
  For best results, plot numerical data by hand on proper bivariate charts.

MB=Mature Bch; Sett=Settling (Closed Basin); Tflat=Tidal Flat; GLF=Glacio-Fluv.
Parameter (below)                  Environment:  Dune  MB  Riv  Sett TFlat GLF
      Procedures giving 1 or 2 answers:    . . . . . . . . . . . . . . . . . . .

Mean of the Skewness:                              x               x
Variability diagram:                               x    x
      Procedures generally giving one answer:  . . . . . . . . . . . . . . . . .
RelDisMn vs RelDisStdDev:                               X
Mean of the Tails-of-Fines:                        X
StdDev of Tail-of-Fines:                           X
Tail-of-Fines diagram:                             X
Inverted RelDisp (Sk vs K; Min. usefulness):                       x
Eolian hump (definitive!):                         X



This is SUITES.  Data source: kirk-gsd.7p5.  N = 21 ,  1  to  21 . 02-24-1995

The End.
```

Figure 36. (cont.)



```
This is SUITES. Data source: stormrdg.5p5.  No. of Samples:  21 .  02-27-1995

This program produces suite, or group, statistics  for a suite, or set, of
samples, presumably all representing the same depositional environment.
                                  Panel 1

Tabulation of data:

Sample       Mean   Std.Dev.  Skewness  Kurtosis   5thM.M.   6thM.M.    T.of F.
SJ89-20      2.012    .338      .061      3.399     1         1         .00029
SJ89-21      2.039    .317      .143      3.744     1         1         .00031
SJ89-22      1.973    .347     -.01       3.797     1         1         .00036
SJ89-23      1.88     .29       .124      3.974     1         1         .0002
SJ89-24      1.932    .302      .085      3.745     1         1         .00021
SJ89-25      2.114    .256      .192      4.359     1         1         .00024
SJ89-26      2.043    .338      .057      3.033     1         1         .00019
SJ89-27      2.247    .286      .063      3.533     1         1         .00017
SJ89-28      2.085    .274     -.038      3.837     1         1         .00014
SJ89-29      1.914    .34      -.187      3.264     1         1         .00012
SJ89-30      2.253    .289     -.087      3.507     1         1         .00019
SJ89-31      2.239    .269      .039      3.771     1         1         .00017
SJ89-32      2.158    .261      .162      4.015     1         1         .00027
SJ89-33      2.068    .337     -.081      3.308     1         1         .00028
SJ89-34      2.036    .342      .113      2.765     1         1         .00016
SJ89-35      1.951    .354     -.033      3.066     1         1         .00017
SJ89-36      1.88     .327      .127      3.147     1         1         .00012
SJ89-37      2.105    .293      .051      3.727     1         1         .0003
SJ89-38      2.067    .346     -.1        3.341     1         1         .00015
SJ89-39      2.08     .345     -.195      3.263     1         1         .00013
SJ89-40      2.109    .332     -.014      3.358     1         1         .0002
Sample       Mean  Std.Dev.  Skewness  Kurtosis   5thM.M.   6thM.M.    T.of F.
                                  Panel 2

     Suite homogeneity, in terms of departures of sample means and
standard deviations from the suite mean values (of means & std.devs.)
as an evaluation of uniformity.  Crosses represent numbers on far right.
Mean and Std. Dev. of Means:  2.056  .108   and of Std.Devs.:  .313  .031

Std.Dv.  Dep.of Std.D.     -.5        .0.        +.5              Dep. of Mean
 .354    .041                       +                                 -.106
 .347    .034                       +                                 -.083
 .345    .032                         +                                .009
 .344    .032                         +                                .023
 .342    .029                         +                                -.02
 .34     .027                      +                                  -.143
 .337    .025                        +                                -.044
 .337    .025                         +                               -.015
 .337    .024                         +                                .012
 .331    .018                          +                               .052
 .326    .013                     +                                   -.176
 .317    .004                         +                               -.018
 .301   -.012                       +                                 -.124
 .293   -.02                           +                               .048
 .289   -.024                     +                                   -.176
 .289   -.024                            +                             .196
 .286   -.027                            +                             .189
 .273   -.04                           +                               .028
 .268   -.044                            +                             .182
 .261   -.052                          +                               .101
 .256   -.057                         +                                .057
Std.Dv.  Dep.of Std.D.     -.5        .0.        +.5              Dep. of Mean

Evaluation of homogeneity.   Crosses represent numbers on far right.
   Outliers, if any, should be obvious.  Data Source: stormrdg.5p5
If any point needs to be removed from the suite, the program should
be run again with a reduced number of samples.
```

Figure 37. Example of SUITES output for the Storm Ridge deposit of St. Joseph Peninsula, Florida.



```
This is SUITES.     Results:
                                    Panel 3
The sequence of results, for each parameter such as the mean, is:
six moment measures, then percent on the 4-phi-sieve-and-finer.
That is, the first line refers to the mean of the means, mean of
the standard deviations, mean of the skewnesses, etc.
    Source of data stormrdg.5p5.   N=  21 .  Samples, 1  to  21

              Means   Std.Dev.  Skewn.   Kurtos.  5th.M.M.   6th.M.M.  T.Fines
Mean of the:   2.056     .313     .022     3.521    0          0          .0002

Stnd. Dev.:    .108      .031     .106     .374     0          0         0
Skewness:      .166     -.431    -.45      .132     0          0          .601
Kurtosis:      2.335     1.702    2.344    2.62     0          0          2.295

Fifth Mom.:    .984     -1.646   -2.393    1.047    0          0          3.015

Sixth Mom.:    6.327     3.934    7.511    10.114   0          0          7.957

Rel.Disp.:     .052      .1       4.751    .106     0          0          .324
Invrtd.R.D.:   18.937    9.989    .21      9.41     0          0         3.082
        StdDev/Ku. =  .088 .    Kurt./Mean =  1.712 .
                T.of F. Mns & StdDevs as Percent:  .02 ;    0
Mn & StdDev of Mn/Ku & of SD/Ku:    .583  .063 .       .089  .017

    The Relative Dispersion (or Coefficient of Variation) is the
    Standard Deviation divided by the Mean.
                                    Panel 4
The primary use of the next display is to minimize the weight of certain
interpretations (e.g., no X's).  Of those that are left, a single line
with 2 X's must not be taken to demonstrate either one alone; FIRST,
identify SINGLE-X lines and their site meanings.    NOTE that the
Tail-of-Fines tends to identify the last-previous agency.
  For best results, plot numerical data by hand on proper bivariate charts.

MB=Mature Bch; Sett=Settling (Closed Basin); Tflat=Tidal Flat; GLF=Glacio-Fluv.
Parameter (below)               Environment:  Dune   MB  Riv  Sett TFlat GLF
      Procedures giving 1 or 2 answers:  . . . . . . . . . . . . . . . . . . .

Mean of the Skewness:                                 x   x
Variability diagram:                             x    x
      Procedures generally giving one answer:   . . . . . . . . . . . . . . . .
RelDisMn vs RelDisStdDev:                                      X
Mean of the Tails-of-Fines:                           X
StdDev. of Tail-of-Fines:                             X
Tail-of-Fines diagram:                                X


The Storm Ridge on St. Joseph Peninsula, FL.  Tall ridge.

This is SUITES.  Data source: stormrdg.5p5.  N = 21 ,  1  to  21 . 02-27-1995

The End.
```

Figure 37. (cont.)

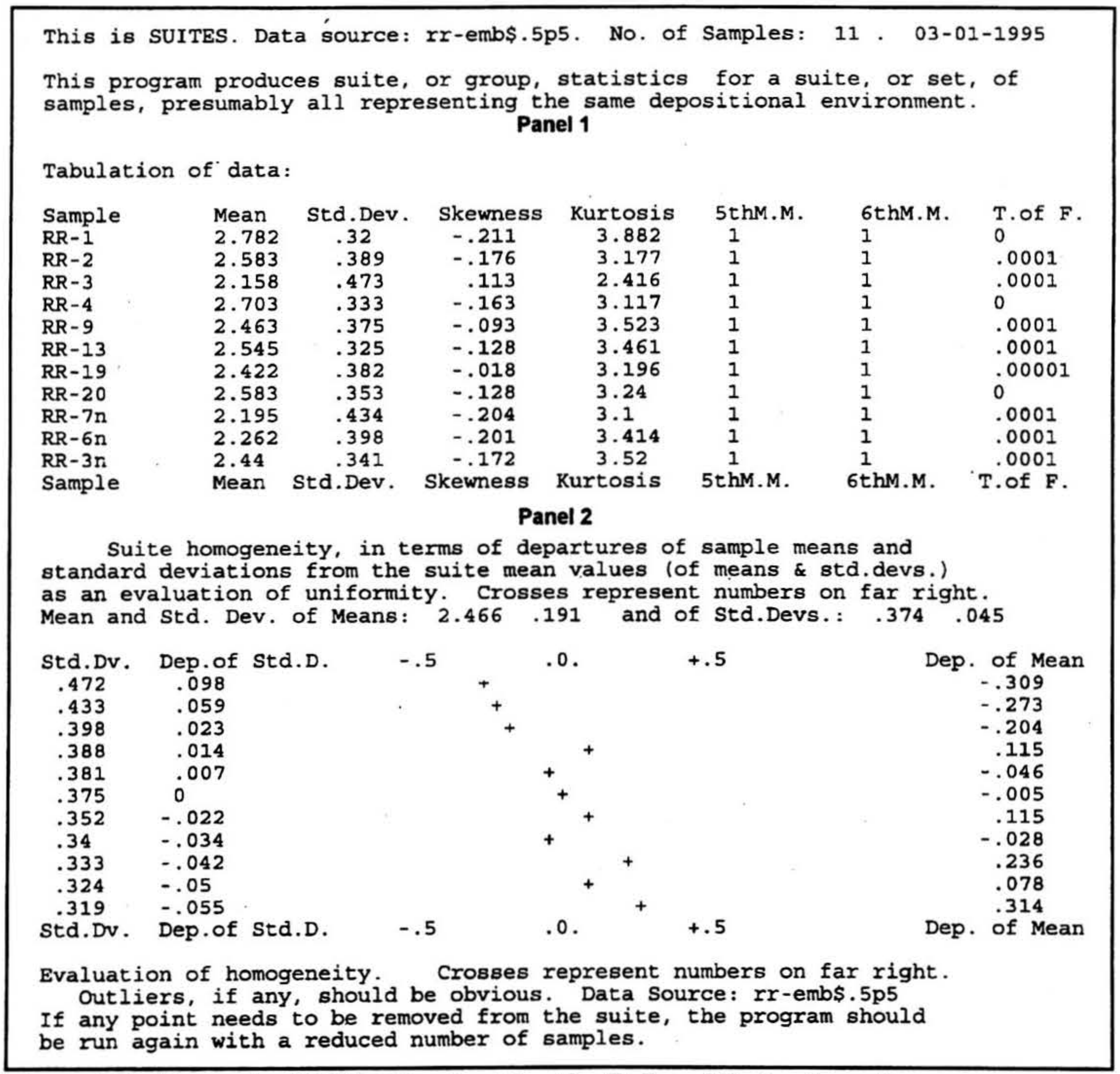
arbitrarily set at 5 Φ.]

Panel 4 indicates that the deposit is a high energy mature beach. It is the additional field information that suggests it is storm produced.

It may be of interest to note that while storms and hurricanes are primarily erosive agents, Balsillie (1985, p. 33-34) found from 249 first quadrant (in terms of event impact) beach and nearshore profiles for 3 hurricanes and 2 storms that, on the average, 16% of the area impacted by the extreme events resulted in accretion. The standard deviation for these data was only 0.059%! It is also interesting that the volume of sand accreted during the storms was 27% of the eroded volume (i.e., TYPE I erosion where accretion was not even considered). This is a rather large volume considering that but 16% of the impacted area(s) experienced accretion. Furthermore, there is no singular area within the 1st quadrant where accretion occurs; rather, it appears to be random.

Example 3. The Railroad Embankment, Gulf County, Florida.

The Railroad Embankment is located in Gulf County just to the east of Cape San Blas (see Figure 41 for an approximate location - locale RREMB). It is a ridge with 4 or 5 meters of relief, and is comprised of parallel to sub-parallel, low-angle, cross-bedding planes sloping 6 to 8 degrees down in the seaward direction. It, again, shows good homogeneity (Figure 38)



```
This is SUITES. Data source: rr-emb$.5p5.  No. of Samples:  11 .  03-01-1995

This program produces suite, or group, statistics  for a suite, or set, of
samples, presumably all representing the same depositional environment.
                                    Panel 1

Tabulation of data:

Sample       Mean   Std.Dev.  Skewness  Kurtosis   5thM.M.    6thM.M.   T.of F.
RR-1         2.782    .32      -.211      3.882     1         1         0
RR-2         2.583   .389      -.176      3.177     1         1         .0001
RR-3         2.158   .473       .113      2.416     1         1         .0001
RR-4         2.703   .333      -.163      3.117     1         1         0
RR-9         2.463   .375      -.093      3.523     1         1         .0001
RR-13        2.545   .325      -.128      3.461     1         1         .0001
RR-19        2.422   .382      -.018      3.196     1         1         .00001
RR-20        2.583   .353      -.128      3.24      1         1         0
RR-7n        2.195   .434      -.204      3.1       1         1         .0001
RR-6n        2.262   .398      -.201      3.414     1         1         .0001
RR-3n        2.44    .341      -.172      3.52      1         1         .0001
Sample       Mean  Std.Dev.  Skewness  Kurtosis   5thM.M.    6thM.M.   T.of F.
                                    Panel 2
     Suite homogeneity, in terms of departures of sample means and
standard deviations from the suite mean values (of means & std.devs.)
as an evaluation of uniformity.  Crosses represent numbers on far right.
Mean and Std. Dev. of Means:  2.466  .191   and of Std.Devs.:  .374  .045

Std.Dv.  Dep.of Std.D.      -.5        .0.        +.5              Dep. of Mean
 .472     .098                   +                                       -.309
 .433     .059                    +                                      -.273
 .398     .023                     +                                     -.204
 .388     .014                           +                                .115
 .381     .007                        +                                  -.046
 .375    0                             +                                 -.005
 .352    -.022                           +                                .115
 .34     -.034                        +                                  -.028
 .333    -.042                              +                             .236
 .324    -.05                            +                                .078
 .319    -.055                               +                            .314
Std.Dv.  Dep.of Std.D.      -.5        .0.        +.5              Dep. of Mean

Evaluation of homogeneity.    Crosses represent numbers on far right.
   Outliers, if any, should be obvious.  Data Source: rr-emb$.5p5
If any point needs to be removed from the suite, the program should
be run again with a reduced number of samples.
```

Figure 38. Example of SUITES output for the Railroad Embankment.

```
                                     Panel 3
This is SUITES.     Results:

The sequence of results, for each parameter such as the mean, is:
six moment measures, then percent on the 4-phi-sieve-and-finer.
That is, the first line refers to the mean of the means, mean of
the standard deviations, mean of the skewnesses, etc.
    Source of data rr-emb$.5p5.   N=  11 .  Samples, 1  to  11

              Means    Std.Dev.  Skewn.   Kurtos.  5th.M.M.   6th.M.M.  T.Fines
Mean of the:   2.466     .374    -.126     3.276    0           0          0
Stnd. Dev.:     .191     .045     .092     .35      0           0          0
Skewness:     -.134      .731     1.481   -.82      0           0        -.577
Kurtosis:      2.02      2.654    4.295    4.16     0           0          1.343

Fifth Mom.:   -.277      4.131    10.234  -6.667    0           0        -1.372

Sixth Mom.:    4.657     10.105   26.508   22.244   0           0          2.175

Rel.Disp.:      .077     .121    -.74      .107     0           0           .727
Invrtd.R.D.:   12.901    8.235   -1.353    9.338    0           0          1.374
        StdDev/Ku. =  .114 .    Kurt./Mean =  1.328 .
                T.of F. Mns & StdDevs as Percent:  0 ;    0
Mn & StdDev of Mn/Ku & of SD/Ku:     .752  .071 .      .114  .029

    The Relative Dispersion (or Coefficient of Variation) is the
    Standard Deviation divided by the Mean.
                                     Panel 4
The primary use of the next display is to minimize the weight of certain
interpretations (e.g., no X's).  Of those that are left, a single line
with 2 X's must not be taken to demonstrate either one alone; FIRST,
identify SINGLE-X lines and their site meanings.    NOTE that the
Tail-of-Fines tends to identify the last-previous agency.
  For best results, plot numerical data by hand on proper bivariate charts.

MB=Mature Bch; Sett=Settling (Closed Basin); Tflat=Tidal Flat; GLF=Glacio-Fluv.
Parameter (below)                Environment:   Dune   MB  Riv  Sett TFlat GLF
      Procedures giving 1 or 2 answers:   . . . . . . . . . . . . . . . . . . .

Mean of the Skewness:                              x   x
Variability diagram:                          x    x
      Procedures generally giving one answer:   . . . . . . . . . . . . . . . .
RelDisMn vs RelDisStdDev:                          X
Mean of the Tails-of-Fines:                        X
StdDev. of Tail-of-Fines:                          X
Tail-of-Fines diagram:                             X
Inverted RelDisp (Sk vs K; Min. usefulness:            x


Railroad Embankment, near Cape San Blas, FL.  Tall. ridge

This is SUITES.  Data source: rr-emb$.5p5.  N = 11 ,  1  to  11 . 03-01-1995

The End.
```

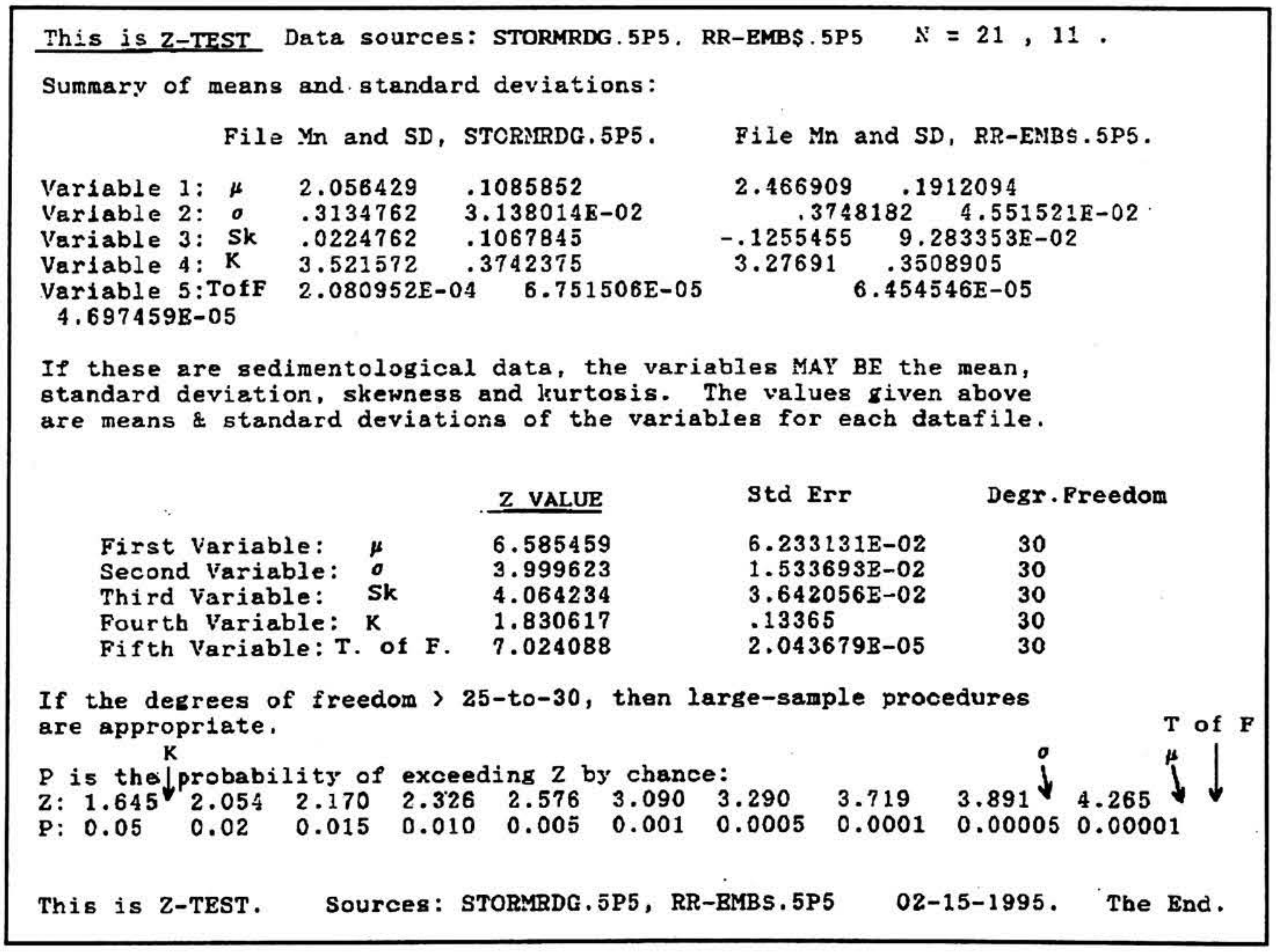
Figure 38. (cont.)

according to panel 2 of the SUITES program. The environmental interpretation of panel 4 indicates, with no question, that the deposit is mature beach. [NOTE: probability plots did show the highly diagnostic surf-break which was not interactively logged in the SUITES data entry section.] The Railroad Embankment is a fair-weather swash/runup deposit, or beach ridge.

The Storm Ridge versus the Railroad Embankment and the Z-Test.

Interpretation of granulometric results of the SUITES program clearly identifying both deposits to be mature beach. Additional field evidence, as we have seen (e.g., bedding types and slopes), indicate that they are different. Is there any other way that would indicate a difference? Yes, probability applications can be employed. Results from a Z-Test are listed in Table 6. The Z-Test determines the degree of difference between averages, in this case suite means for the first 4 moment measures. The number of samples for the Storm Ridge (STORMRDG.5P5) was 21, with 11 samples comprising the suite representing the Railroad Embankment (RR-EMB$.5P5). Input data are listed under the heading "summary of means and standard deviations". The column with the header "Z VALUE" lists the Z value results; the larger the Z value, the greater the statistical difference between averages tested. Exceedence probability and significance of the Z-Test results are shown by the Z and P rows near the bottom of the table. Moment measures for σ, μ, and the tail-of-fines (T of F) are significantly different to the less than 0.00005 confidence level, K is significantly different to less than the 0.05 confidence level. Hence, the two deposits are not the same.

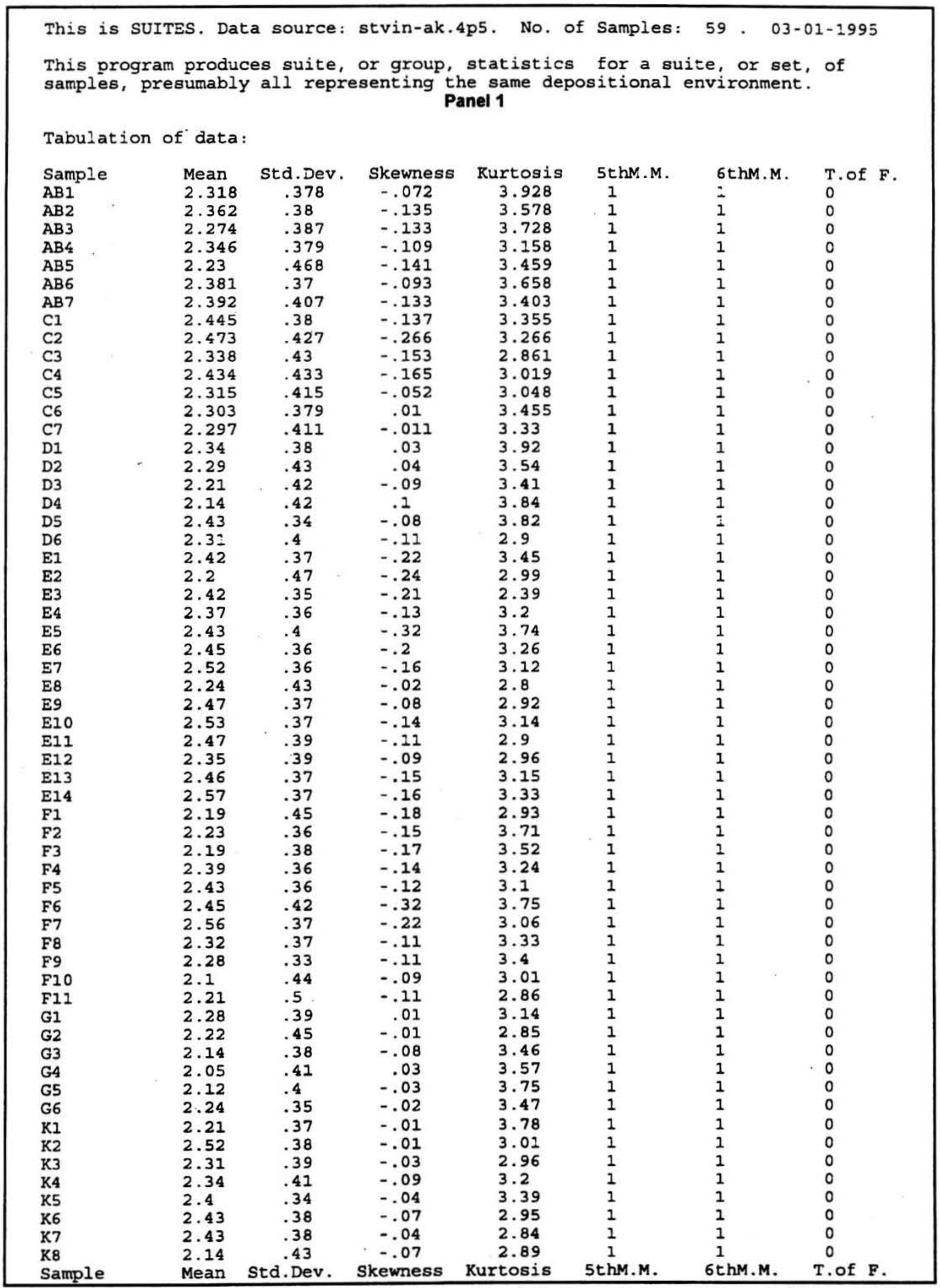
Table 6. Z-Test for the Storm Ridge (STORMRDG.5P5) and Railroad Embankment (RR-EMB$.5P5) deposits of Gulf County, Florida.



```
This is Z-TEST  Data sources: STORMRDG.5P5. RR-EMB$.5P5    N = 21 , 11 .

Summary of means and standard deviations:

            File Mn and SD, STORMRDG.5P5.      File Mn and SD, RR-EMBS.5P5.

Variable 1: μ     2.056429   .1085852          2.466909   .1912094
Variable 2: σ     .3134762   3.138014E-02        .3748182   4.551521E-02
Variable 3: Sk    .0224762   .1067845         -.1255455   9.283353E-02
Variable 4: K     3.521572   .3742375          3.27691   .3508905
Variable 5:TofF   2.080952E-04   6.751506E-05           6.454546E-05
 4.697459E-05

If these are sedimentological data, the variables MAY BE the mean,
standard deviation, skewness and kurtosis.  The values given above
are means & standard deviations of the variables for each datafile.


                                Z VALUE         Std Err         Degr.Freedom

    First Variable:    μ        6.585459        6.233131E-02      30
    Second Variable:   σ        3.999623        1.533693E-02      30
    Third Variable:    Sk       4.064234        3.642056E-02      30
    Fourth Variable:  K         1.830617        .13365            30
    Fifth Variable: T. of F.    7.024088        2.043679E-05      30

If the degrees of freedom > 25-to-30, then large-sample procedures
are appropriate.                                                         T of F
        K                                                        σ      μ
P is the↓probability of exceeding Z by chance:                   ↓      ↓  ↓
Z: 1.645  2.054  2.170  2.326  2.576  3.090  3.290   3.719   3.891  4.265
P: 0.05   0.02   0.015  0.010  0.005  0.001  0.0005  0.0001  0.00005 0.00001


This is Z-TEST.    Sources: STORMRDG.5P5, RR-EMBS.5P5    02-15-1995.  The End.
```

Example 4. The St. Vincent Island Beach Ridge Plain.

It would be remiss if we did not show SUITES results for the classic St. Vincent Island Beach Ridge Plain. Results for all 59 individual ridges for the plain are given by Figure 39. Again, the homogeneity (panel 2) is very good. Panel 4 overwhelmingly indicates that the



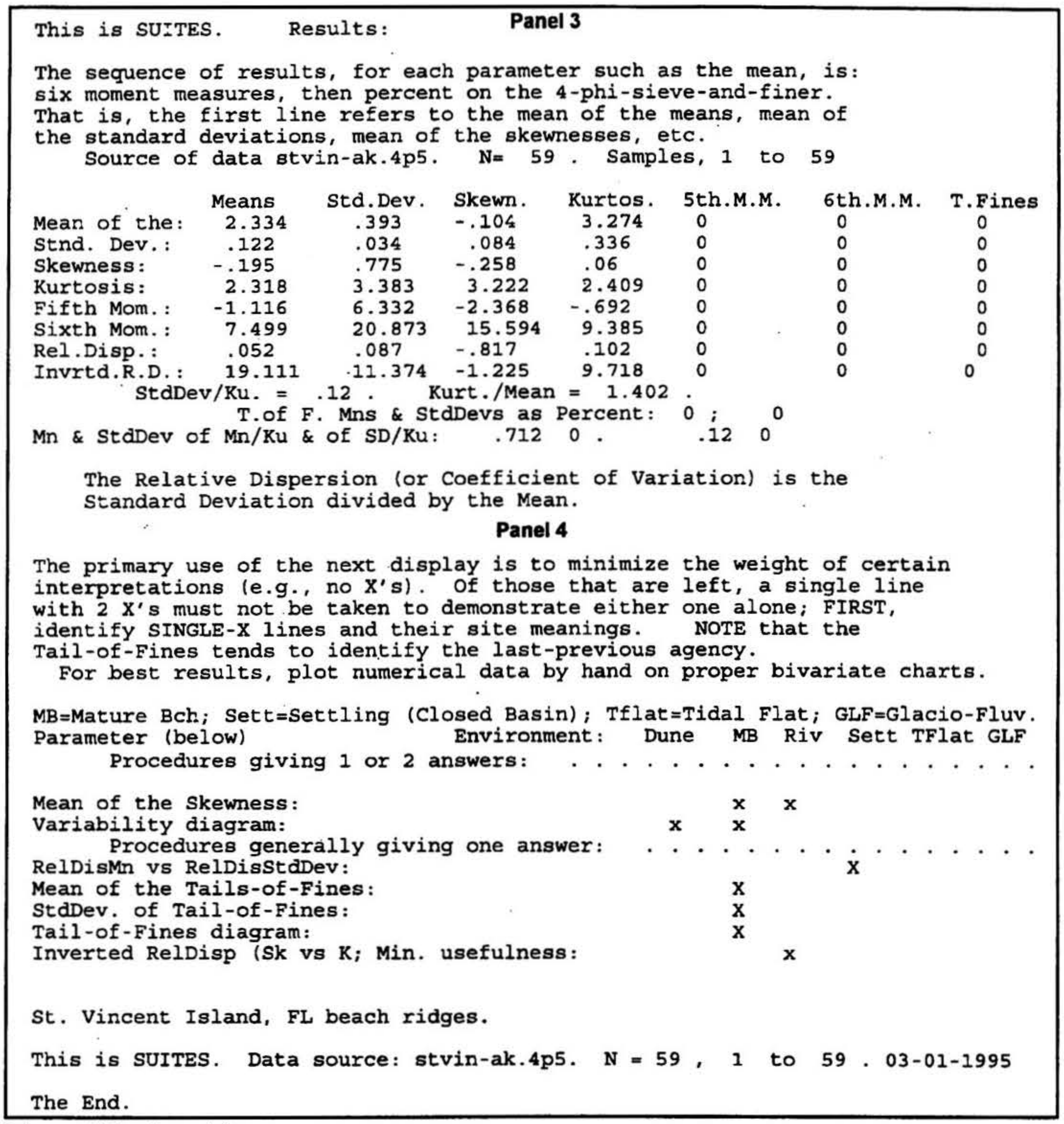
```
This is SUITES. Data source: stvin-ak.4p5.  No. of Samples:  59 .  03-01-1995

This program produces suite, or group, statistics  for a suite, or set, of
samples, presumably all representing the same depositional environment.
                                  Panel 1

Tabulation of data:

Sample        Mean    Std.Dev.   Skewness  Kurtosis   5thM.M.    6thM.M.   T.of F.
AB1           2.318    .378      -.072      3.928      1          1          0
AB2           2.362    .38       -.135      3.578      1          1          0
AB3           2.274    .387      -.133      3.728      1          1          0
AB4           2.346    .379      -.109      3.158      1          1          0
AB5           2.23     .468      -.141      3.459      1          1          0
AB6           2.381    .37       -.093      3.658      1          1          0
AB7           2.392    .407      -.133      3.403      1          1          0
C1            2.445    .38       -.137      3.355      1          1          0
C2            2.473    .427      -.266      3.266      1          1          0
C3            2.338    .43       -.153      2.861      1          1          0
C4            2.434    .433      -.165      3.019      1          1          0
C5            2.315    .415      -.052      3.048      1          1          0
C6            2.303    .379       .01       3.455      1          1          0
C7            2.297    .411      -.011      3.33       1          1          0
D1            2.34     .38        .03       3.92       1          1          0
D2            2.29     .43        .04       3.54       1          1          0
D3            2.21     .42       -.09       3.41       1          1          0
D4            2.14     .42        .1        3.84       1          1          0
D5            2.43     .34       -.08       3.82       1          1          0
D6            2.31     .4        -.11       2.9        1          1          0
E1            2.42     .37       -.22       3.45       1          1          0
E2            2.2      .47       -.24       2.99       1          1          0
E3            2.42     .35       -.21       2.39       1          1          0
E4            2.37     .36       -.13       3.2        1          1          0
E5            2.43     .4        -.32       3.74       1          1          0
E6            2.45     .36       -.2        3.26       1          1          0
E7            2.52     .36       -.16       3.12       1          1          0
E8            2.24     .43       -.02       2.8        1          1          0
E9            2.47     .37       -.08       2.92       1          1          0
E10           2.53     .37       -.14       3.14       1          1          0
E11           2.47     .39       -.11       2.9        1          1          0
E12           2.35     .39       -.09       2.96       1          1          0
E13           2.46     .37       -.15       3.15       1          1          0
E14           2.57     .37       -.16       3.33       1          1          0
F1            2.19     .45       -.18       2.93       1          1          0
F2            2.23     .36       -.15       3.71       1          1          0
F3            2.19     .38       -.17       3.52       1          1          0
F4            2.39     .36       -.14       3.24       1          1          0
F5            2.43     .36       -.12       3.1        1          1          0
F6            2.45     .42       -.32       3.75       1          1          0
F7            2.56     .37       -.22       3.06       1          1          0
F8            2.32     .37       -.11       3.33       1          1          0
F9            2.28     .33       -.11       3.4        1          1          0
F10           2.1      .44       -.09       3.01       1          1          0
F11           2.21     .5        -.11       2.86       1          1          0
G1            2.28     .39        .01       3.14       1          1          0
G2            2.22     .45       -.01       2.85       1          1          0
G3            2.14     .38       -.08       3.46       1          1          0
G4            2.05     .41        .03       3.57       1          1          0
G5            2.12     .4        -.03       3.75       1          1          0
G6            2.24     .35       -.02       3.47       1          1          0
K1            2.21     .37       -.01       3.78       1          1          0
K2            2.52     .38       -.01       3.01       1          1          0
K3            2.31     .39       -.03       2.96       1          1          0
K4            2.34     .41       -.09       3.2        1          1          0
K5            2.4      .34       -.04       3.39       1          1          0
K6            2.43     .38       -.07       2.95       1          1          0
K7            2.43     .38       -.04       2.84       1          1          0
K8            2.14     .43       -.07       2.89       1          1          0
Sample        Mean  Std.Dev.   Skewness  Kurtosis   5thM.M.    6thM.M.   T.of F.
```

Figure 39. Example of SUITES output for the St Viincent Island Beach Ridge Plain.

Panel 2

```
     Suite homogeneity, in terms of departures of sample means and
standard deviations from the suite mean values (of means & std.devs.)
as an evaluation of uniformity.  Crosses represent numbers on far right.
Mean and Std. Dev. of Means:  2.334  .122    and of Std.Devs.:  .393  .034

Std.Dv.  Dep.of Std.D.     -.5        .0.        +.5               Dep. of Mean
 .5       .106                       +                                 -.125
 .469     .076                      +                                  -.136
 .467     .074                       +                                 -.105
 .449     .056                       +                                 -.116
 .449     .056                      +                                  -.145
 .439     .046                    +                                    -.235
 .432     .039                           +                              .098
 .43      .037                     +                                   -.195
 .43      .037                        +                                -.046
 .43      .037                         +                                .003
 .43      .037                       +                                 -.095
 .426     .033                            +                             .137
 .419     .026                           +                              .115
 .419     .026                     +                                   -.195
 .419     .026                       +                                 -.125
 .414     .021                         +                                -.02
 .411     .018                        +                                -.038
 .409     .016                   +                                     -.285
 .409     .016                         +                                .004
 .407     .013                          +                               .057
 .4       .006                           +                              .094
 .4       .006                     +                                   -.216
 .4       .006                         +                               -.026
 .389    -.004                         +                                .014
 .389    -.004                        +                                -.055
 .389    -.004                            +                             .135
 .389    -.004                         +                               -.026
 .386    -.007                        +                                -.062
 .379    -.014                           +                              .094
 .379    -.014                           +                              .094
 .379    -.014                      +                                  -.145
 .379    -.014                             +                            .185
 .379    -.014                          +                               .027
 .379    -.014                           +                              .109
 .379    -.014                     +                                   -.195
 .379    -.014                         +                                .004
 .379    -.014                         +                                .01
 .379    -.014                        +                                -.033
 .377    -.016                         +                               -.018
 .37     -.024                              +                           .234
 .37     -.024                       +                                 -.125
 .37     -.024                           +                              .125
 .37     -.024                             +                            .194
 .37     -.024                         +                               -.015
 .37     -.024                             +                            .224
 .37     -.024                            +                             .135
 .37     -.024                           +                              .085
 .37     -.024                          +                               .046
 .36     -.033                             +                            .185
 .36     -.033                           +                              .115
 .36     -.033                          +                               .035
 .36     -.033                           +                              .094
 .36     -.033                          +                               .054
 .36     -.033                       +                                 -.105
 .349    -.044                           +                              .085
 .349    -.044                       +                                 -.095
 .34     -.054                          +                               .064
 .34     -.054                           +                              .094
 .33     -.063                        +                                -.055
Std.Dv.  Dep.of Std.D.     -.5        .0.        +.5               Dep. of Mean

Evaluation of homogeneity.    Crosses represent numbers on far right.
   Outliers, if any, should be obvious.  Data Source: stvin-ak.4p5
If any point needs to be removed from the suite, the program should
be run again with a reduced number of samples.
```

Figure 39. (cont.)

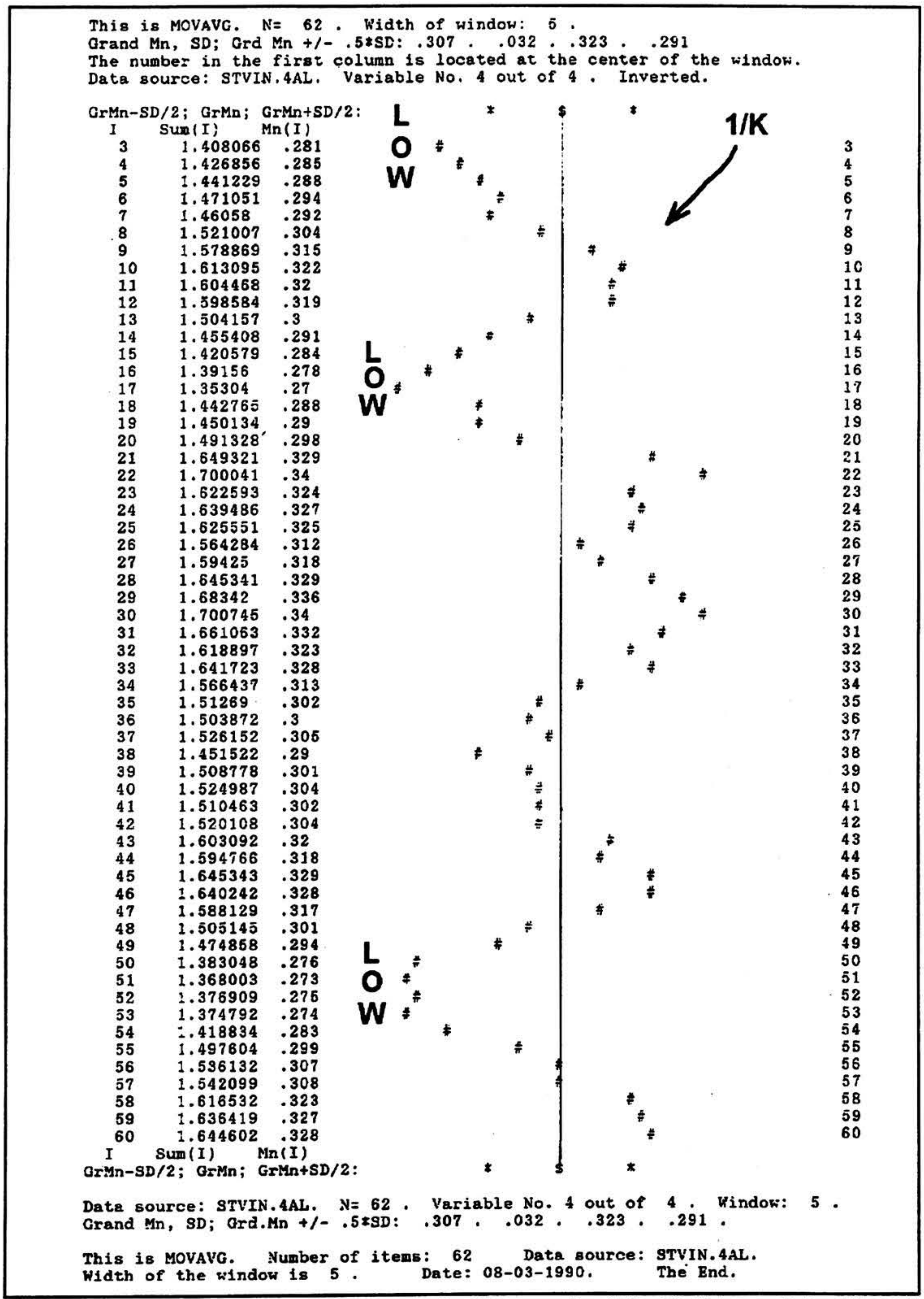


```
This is SUITES.     Results:           Panel 3

The sequence of results, for each parameter such as the mean, is:
six moment measures, then percent on the 4-phi-sieve-and-finer.
That is, the first line refers to the mean of the means, mean of
the standard deviations, mean of the skewnesses, etc.
    Source of data stvin-ak.4p5.   N=  59 .  Samples, 1  to  59

              Means     Std.Dev.  Skewn.    Kurtos.  5th.M.M.     6th.M.M.   T.Fines
Mean of the:   2.334      .393    -.104      3.274    0             0          0
Stnd. Dev.:    .122       .034     .084      .336     0             0          0
Skewness:     -.195       .775    -.258      .06      0             0          0
Kurtosis:      2.318      3.383    3.222     2.409    0             0          0
Fifth Mom.:   -1.116      6.332   -2.368    -.692     0             0          0
Sixth Mom.:    7.499      20.873   15.594    9.385    0             0          0
Rel.Disp.:     .052       .087    -.817      .102     0             0          0
Invrtd.R.D.:   19.111     11.374  -1.225     9.718    0             0         0
        StdDev/Ku. =  .12 .     Kurt./Mean =  1.402 .
                T.of F. Mns & StdDevs as Percent:  0 ;    0
Mn & StdDev of Mn/Ku & of SD/Ku:     .712  0 .        .12  0

    The Relative Dispersion (or Coefficient of Variation) is the
    Standard Deviation divided by the Mean.
                                    Panel 4
The primary use of the next display is to minimize the weight of certain
interpretations (e.g., no X's).  Of those that are left, a single line
with 2 X's must not be taken to demonstrate either one alone; FIRST,
identify SINGLE-X lines and their site meanings.   NOTE that the
Tail-of-Fines tends to identify the last-previous agency.
  For best results, plot numerical data by hand on proper bivariate charts.

MB=Mature Bch; Sett=Settling (Closed Basin); Tflat=Tidal Flat; GLF=Glacio-Fluv.
Parameter (below)                  Environment:  Dune   MB  Riv  Sett TFlat GLF
      Procedures giving 1 or 2 answers:  . . . . . . . . . . . . . . . . . . .

Mean of the Skewness:                                   x   x
Variability diagram:                             x      x
      Procedures generally giving one answer:   . . . . . . . . . . . . . . . .
RelDisMn vs RelDisStdDev:                                        X
Mean of the Tails-of-Fines:                             X
StdDev. of Tail-of-Fines:                               X
Tail-of-Fines diagram:                                  X
Inverted RelDisp (Sk vs K; Min. usefulness:                 x

St. Vincent Island, FL beach ridges.

This is SUITES.  Data source: stvin-ak.4p5.  N = 59 ,  1  to  59 . 03-01-1995

The End.
```

Figure 39. (cont.)

suite of samples represents a mature beach deposit. The majority of probability plots did show the surf-break, although it was not interactively so noted in the SUITES program.

The relationship between 1/K and relatively small sea level changes (1-2 m) for all St. Vincent Island beach ridges is illustrated by Figure 40. Sets are identified depending upon whether sea level was low or high and, therefore, sets were correspondingly low or high.

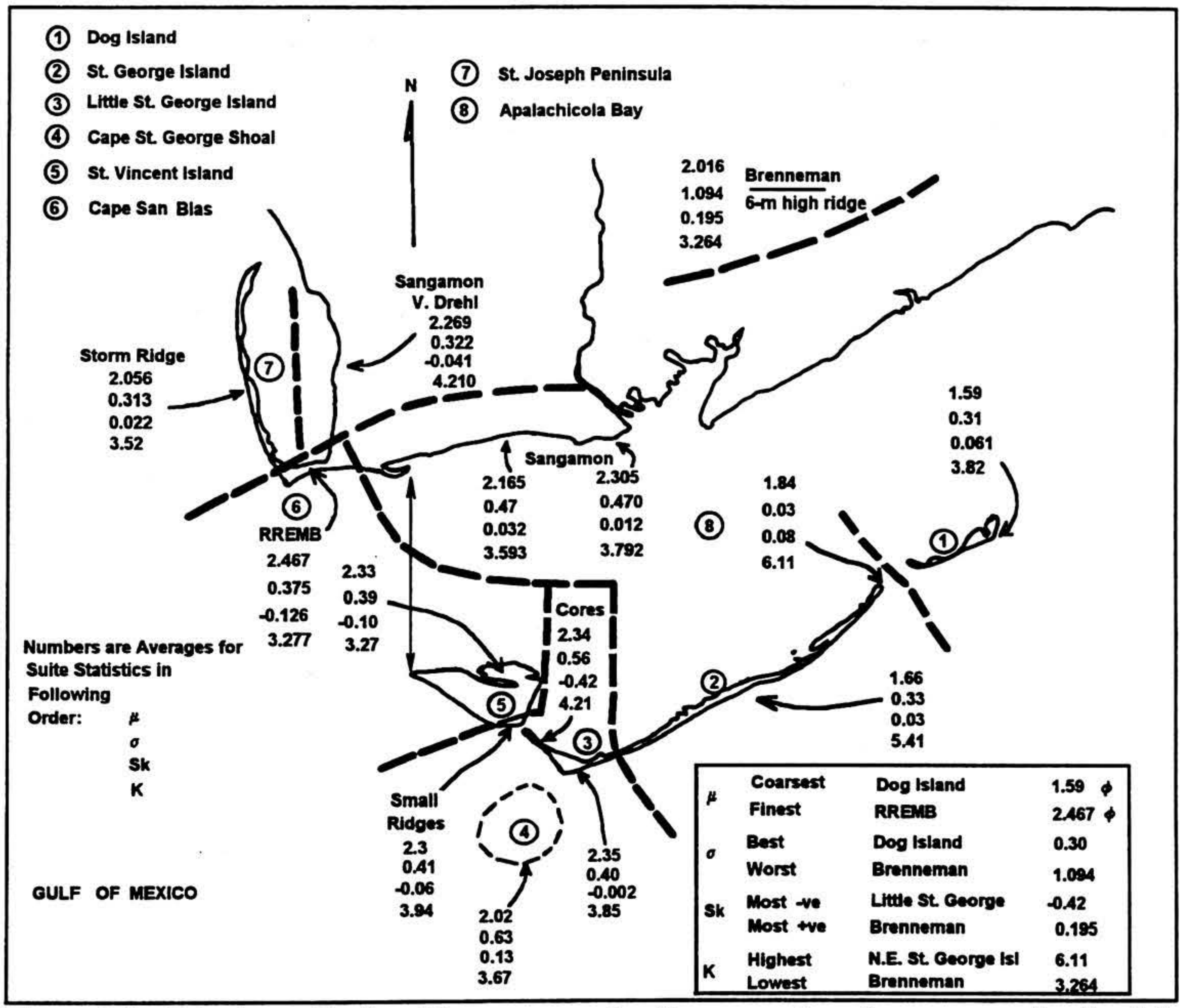


```
This is MOVAVG.  N=  62 .  Width of window:  5 .
Grand Mn, SD; Grd Mn +/- .5*SD: .307 .  .032 . .323 .  .291
The number in the first column is located at the center of the window.
Data source: STVIN.4AL.  Variable No. 4 out of 4 .  Inverted.

GrMn-SD/2; GrMn; GrMn+SD/2:              *       $       *
  I      Sum(I)      Mn(I)
   3     1.408066  .281                                                   3
   4     1.426856  .285                                                   4
   5     1.441229  .288                                                   5
   6     1.471051  .294                                                   6
   7     1.46058   .292                                                   7
  .8     1.521007  .304                                                   8
   9     1.578869  .315                                                   9
  10     1.613095  .322                                                  10
  11     1.604468  .32                                                   11
  12     1.598584  .319                                                  12
  13     1.504157  .3                                                    13
  14     1.455408  .291                                                  14
  15     1.420579  .284                                                  15
  16     1.39156   .278                                                  16
  17     1.35304   .27                                                   17
  18     1.442765  .288                                                  18
  19     1.450134  .29                                                   19
  20     1.491328′ .298                                                  20
  21     1.649321  .329                                                  21
  22     1.700041  .34                                                   22
  23     1.622593  .324                                                  23
  24     1.639486  .327                                                  24
  25     1.625551  .325                                                  25
  26     1.564284  .312                                                  26
  27     1.59425   .318                                                  27
  28     1.645341  .329                                                  28
  29     1.68342   .336                                                  29
  30     1.700745  .34                                                   30
  31     1.661063  .332                                                  31
  32     1.618897  .323                                                  32
  33     1.641723  .328                                                  33
  34     1.566437  .313                                                  34
  35     1.51269   .302                                                  35
  36     1.503872  .3                                                    36
  37     1.526152  .305                                                  37
  38     1.451522  .29                                                   38
  39     1.508778  .301                                                  39
  40     1.524987  .304                                                  40
  41     1.510463  .302                                                  41
  42     1.520108  .304                                                  42
  43     1.603092  .32                                                   43
  44     1.594766  .318                                                  44
  45     1.645343  .329                                                  45
  46     1.640242  .328                                                  46
  47     1.588129  .317                                                  47
  48     1.505145  .301                                                  48
  49     1.474858  .294                                                  49
  50     1.383048  .276                                                  50
  51     1.368003  .273                                                  51
  52     1.376909  .275                                                  52
  53     1.374792  .274                                                  53
  54     1.418834  .283                                                  54
  55     1.497604  .299                                                  55
  56     1.536132  .307                                                  56
  57     1.542099  .308                                                  57
  58     1.616532  .323                                                  58
  59     1.636419  .327                                                  59
  60     1.644602  .328                                                  60
 I     Sum(I)      Mn(I)
GrMn-SD/2; GrMn; GrMn+SD/2:              *       $       *

Data source: STVIN.4AL.  N= 62 .  Variable No. 4 out of  4 .  Window:  5 .
Grand Mn, SD; Grd.Mn +/- .5*SD:  .307 .  .032 .  .323 .  .291 .

This is MOVAVG.   Number of items:  62     Data source: STVIN.4AL.
Width of the window is  5 .      Date: 08-03-1990.     The End.
```

Figure 40. Plot of 1/K for sediment samples from each of the St. Vincent Island beach ridges; data identifies set vertical position changes and, hence, sea-level changes.

Spatial Granulometric Analysis

Probability applications can also be employed to identify geographic distribution of sediments. Pairs of sample suites can be statistically compared using the Z-Test as discussed in the previous section. For example, in Figure 41, fourteen suites of samples have been so analyzed. Analysis of one of the pairs has already been presented in Table 4 for the Storm Ridge versus the Railroad Embankment (RREMB) in which it has been demonstrated that they are two different types of deposits. They have not been deposited by the same transpo-depositional processes. Another interesting pair is found on St. Vincent Island where the classic beach ridges and ridge sets of Figures 31 and 32 are quite different from a set of



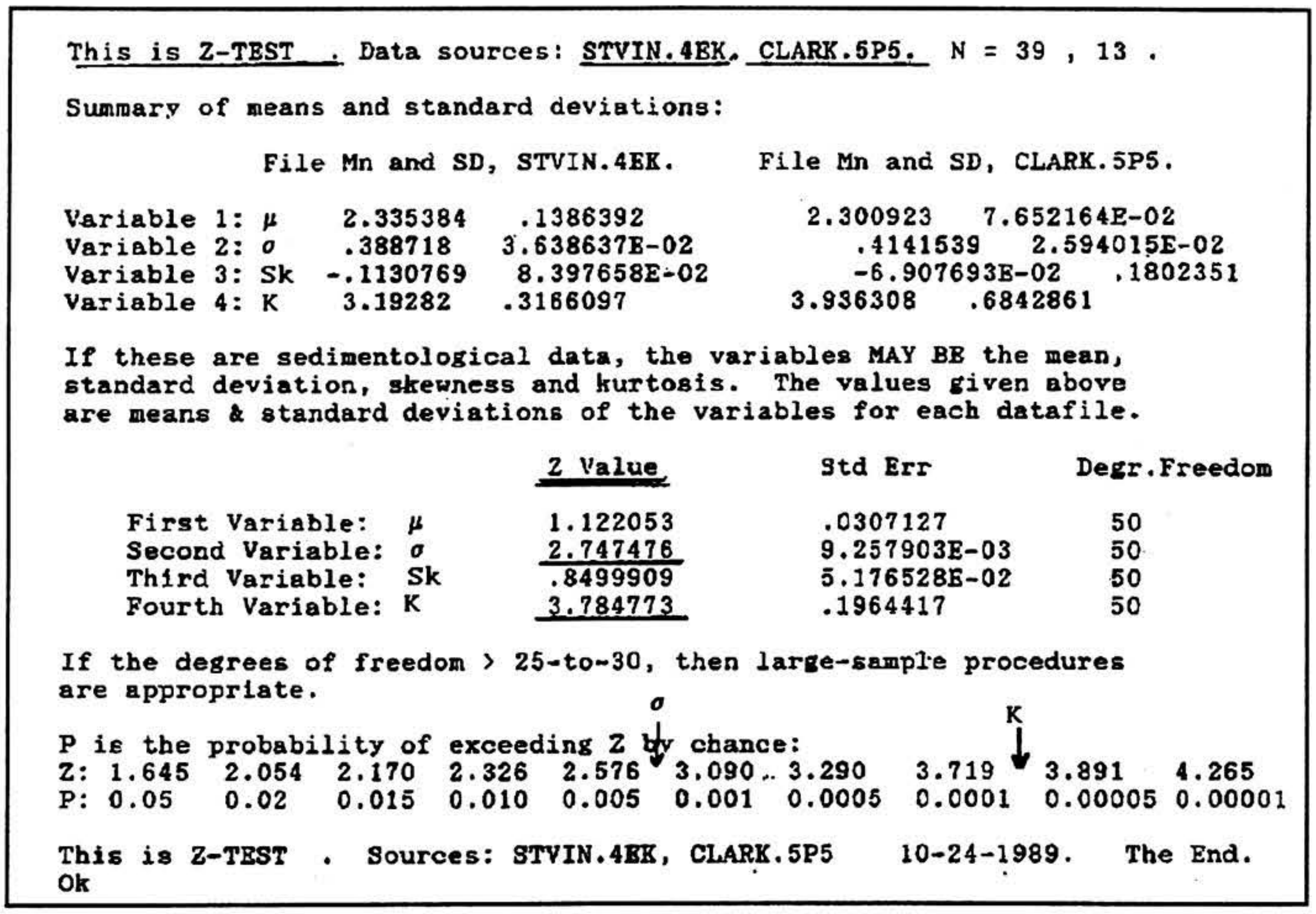
μ	Coarsest	Dog Island	1.59 ϕ
	Finest	RREMB	2.467 ϕ
σ	Best	Dog Island	0.30
	Worst	Brenneman	1.094
Sk	Most -ve	Little St. George	-0.42
	Most +ve	Brenneman	0.195
K	Highest	N.E. St. George Isl	6.11
	Lowest	Brenneman	3.264

Figure 41. Z-test results for phi averages of suite parameters for mean grain size (μ), standard deviation (σ), skewness (Sk), and kurtosis (K) for western panhandle Florida Gulf coast sediments. Paired site means were tested using the Z-test; bold dashed lines represent statistically significant difference between mean values to the standard 0.01 confidence level (actually to the 0.0001 level). Offshore islands have been shifted to the south (narrow vertical line and arrows) to facilitate listings of data.

smaller ridges (labelled small ridges in Figure 41) found along the southeastern tip of the island. Table 7 shows that suite averages for both σ and K are significantly different to less than the 0.005 confidence level. This should be enough evidence to suggest that these ridge sets are different. Sediments from these small ridges are not different from sediment from Little St. George Island. Hence, the small ridges have been deposited by essentially the same depositional agencies that formed Little St. George Island which, in turn, represents a different depositional regime than eastern St. George Island.

The bold dashed lines delineate where areas are different. Z-Test probabilities that these sediment deposits are the same are negligible.

Table 7. Z-Test for St. Vincent Island Beach Ridge Plain (STVIN.4EK) and the southeastern small ridges of St. Vincent Island (CLARK.5P5), Florida.



```
This is Z-TEST  . Data sources: STVIN.4EK, CLARK.5P5.  N = 39 , 13 .

Summary of means and standard deviations:

            File Mn and SD, STVIN.4EK.     File Mn and SD, CLARK.5P5.

Variable 1: μ     2.335384   .1386392          2.300923   7.652164E-02
Variable 2: σ     .388718   3.638637E-02          .4141539   2.594015E-02
Variable 3: Sk  -.1130769   8.397658E-02         -6.907693E-02   .1802351
Variable 4: K     3.19282   .3166097         3.936308   .6842861

If these are sedimentological data, the variables MAY BE the mean,
standard deviation, skewness and kurtosis.  The values given above
are means & standard deviations of the variables for each datafile.

                           Z Value           Std Err          Degr.Freedom

    First Variable:  μ     1.122053          .0307127           50
    Second Variable: σ     2.747476          9.257903E-03       50
    Third Variable:  Sk    .8499909          5.176528E-02       50
    Fourth Variable: K     3.784773          .1964417           50

If the degrees of freedom > 25-to-30, then large-sample procedures
are appropriate.
                                      σ                          K
P is the probability of exceeding Z by chance:
Z: 1.645  2.054  2.170  2.326  2.576  3.090  3.290   3.719   3.891   4.265
P: 0.05   0.02   0.015  0.010  0.005  0.001  0.0005  0.0001  0.00005 0.00001

This is Z-TEST  .  Sources: STVIN.4EK, CLARK.5P5    10-24-1989.   The End.
Ok
```

Review

Employing the granulometric methods that have been presented, we can accomplish at least 7 tasks. These are:

1. The Site:

Although, from time-to-time, it has been requested, one cannot (based on granulometry alone), identify the location where a sample was taken, that is, the beach name, river name, or latitude-longitude.

2. Paleogeography:

Granulometric suite statistics and the inherent variability within is correlative with paleogeographic evidence. For instance, Tanner (1988), demonstrated the correlation for ancient lithified late Pennsylvanian - early Permian sedimentary rocks of central Oklahoma (Figure 42).

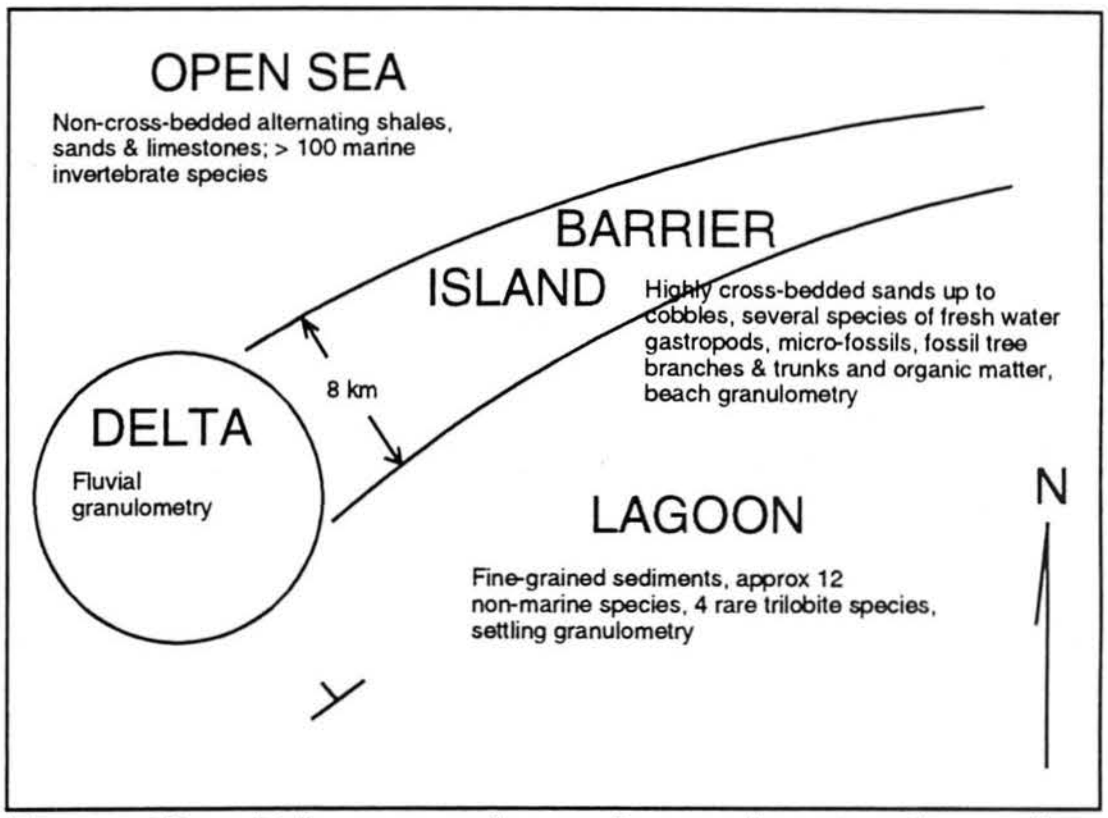


Figure 42. Paleogeography and granulometry for a late Pennsylvanian - early Permian coastal complex in central Oklahoma. The sediment source for the complex was the Arbuckle Mountains lying southeast of the study area.

3. Kurtosis and Hydrodynamics:

If we can identify a mature beach, then the kurtosis will tell us about the wave energy levels at the time the beach was formed.

4. Sand Sources:

The sand source, in terms of its depositional environment, can be determined, and we can distinguish one sediment pool from another. For example, see Figure 41 for the Apalachicola area and the Z-Test.

5. Tracing of Transport Paths:

The coast of Brazil in the vicinity of Rio de Janeiro is characterized by hills of deeply weathered Mesozoic igneous rocks with pocket beaches lying between (see Figure 43). The question has been asked as to the direction of longshore sediment transport. At the outset one would expect to find coarser sediment at the updrift end of a longshore transport cell, becoming finer in the downdrift direction. The subject pocket beaches, however, have finer sediments at the central portion of the beaches, and coarser sediments at the ends of the beaches. Granulometric evidence suggests

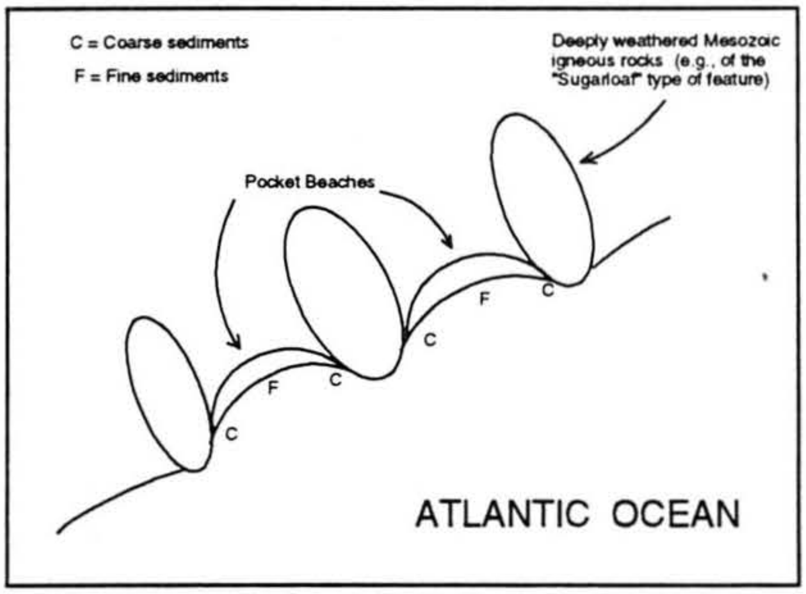


Figure 43. Granulometry and sediment transport paths.

that little, if any, sand is escaping from beach-to-beach in the longshore direction.

6. Sea Level Rise:

Kurtosis correlates inversely with even small changes in sea level (rise and fall). This applies to long-term sea level changes, as well as to extreme event impacts (i.e., hurricanes and storms).

7. Seasonal Changes and Storm/Hurricane Impact:

In the northern hemisphere, astronomical tidal levels are slightly depressed during the winter months relative to summer months. In addition, wave energy levels are normally higher during the winter months. Storm and hurricane impacts result in both high storm tides and wave energy levels. Again, there appears to be an inverse correlation between energy levels for these two examples and the kurtosis, as illustrated by Figure 29. The term "appears" is used because there are not much data available to quantify the relationship, and the reader is encouraged to pursue the collection of such information.

PLOT DECOMPOSITION: MIXING AND SELECTION

On probability paper, quartzose sediment distributions commonly plot as zig-zag lines. Even so, the hypothesis that the basic distribution is Gaussian (i.e., mean = mode = median or 50th percentile) and will, therefore, plot as a straight line remains valid. It is departure from the Gaussian that provides additional characterization of the sediments. Each segment on probability paper is important to consider because it is indicative of a process or processes leading to its appearance. That such identification can be made relating force and response elements using probability paper is not commonly understood. Again, a segment and a component are not the same, although it has been so stated in the literature; a segment must be recalculated to 100% to be a component. Multi-segmented, zig-zag, or multi-component sand distributions have been discussed by a multitude of investigators. However, in a series of papers, Tanner (1964; Appendix X, p. 134) found that zig-zag modifications of the straight-line plot include mixing and selection which, in turn, can be subdivided as follows:

Mixing:
- ◆ Non-zero component
- ◆ Zero component

Selection:
- ◆ Censorship
- ◆ Truncation
- ◆ Filtering

In reality, when we obtain a sand sample it is usually already a mixture of components. In order to determine the components, the distribution must undergo the process of decomposition. It is easier, however, to understand decomposition using the reverse process, e.g., the simple mixing of known component distributions and then determining the resulting total distribution.

Many sedimentologists/soil scientists do not utilize probability paper in the manner presented in this work. They most often use it in a manner that suppresses the very details that we wish to observe. It is W. F. Tanner's opinion that they have not seriously nor carefully thought the issue through.

Simple Mixing

In order to discuss mixing, it helps to specify some conditions such as proportions of mixtures (P), means (μ), and standard deviations (σ).

Non-Zero Component:

Case 1. Let us inspect the case for two component mixing where the proportions are equal, the means differ, and the standard deviations are identical, i.e.,

$P_1 = P_2$
$\mu_1 \neq \mu_2$ [i.e., $\mu_1 > \mu_2$]
$\sigma_1 = \sigma_2$

Plotted components and the resulting mixed distribution are illustrated by Figure 44.

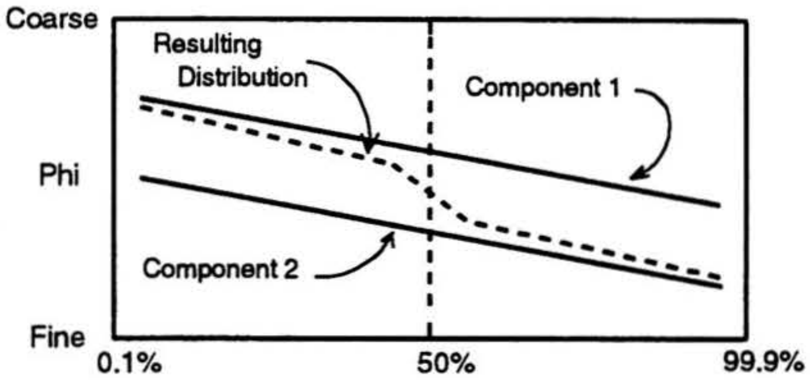


Figure 44. Case 1 example of two-component simple mixing.

The resultant distribution is calculated by adding percentages for each size class and dividing by two. An example for Figure 44 is given by Table 8.

If proportions change, then the combination of curves plotted in Figure 44, will slide either to the right or to the left.

Case 2. Let us make a change in the component characteristics where:

$P_1 = P_2$
$\mu_1 \neq \mu_2$ [i.e., $\mu_1 < \mu_2$]
$\sigma_1 \neq \sigma_2$ [i.e., $\sigma_1 < \sigma_2$]

Component 1 might represent a beach sand, and component 2 a river sand (although it is not

Table 8. Example calculation of component mixing illustrated in Figure 44.

ϕ	Component 1 Cumulative Percent	Component 2 Cumulative Percent	Combined Curve Cumulative Percent
0	0.1	0	0.05
0.25	1.0	0	0.5
0.5	6.0	0	3.0
0.75	21.0	0	10.5
1.00	50.0	0	25.0
1.25	78.0	0	39.0
1.50	94.0	0	47.0
1.75	99.0	0.1	49.55
2.00	99.9	1.0	50.45
2.25	100.0	6.0	53.0
2.50	100.0	21.0	60.5
2.75	100.0	50.0	75.0
3.00	100.0	78.0	89.0
3.25	100.0	94.0	97.0
3.50	100.0	99.0	99.5
3.75	100.0	99.9	99.95

normally possible to have a Gaussian distribution for a fluvial sediment). Would it be possible in nature to have two components of fluvial sediments? The answer is certainly yes; for instance, where two streams meet and one of them has a higher gradient and/or flows across a different lithology than the other, the sediment loads might very well be different. Component 1, however, would more nearly be representative of a beach sand.

Note for cases 1 and 2, that 2 components result in a distribution comprised of 3 segments. There is one instance where 2 components cannot be distinguished from one another ... that occurs where $\mu_1 = \mu_2$ and $\sigma_1 = \sigma_2$, or multiples of such components, regardless of the proportions involved. Now then, if one component is quartz and the other is something different, say olivine, that is a different matter (i.e., chemistry must be considered); or if one is quartz and the other is composed of calcium carbonate shell fragments, then grain shape will affect the outcome. In general, however, the above discourse constitutes the basic preliminary rules for the treatment of simple mixing.

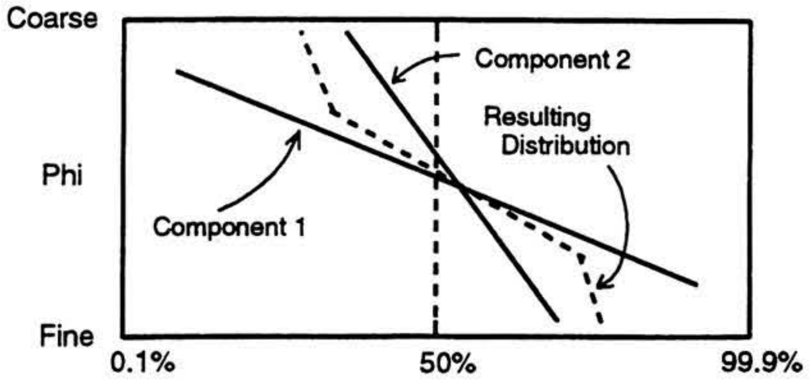


Figure 45. Case 2 example of two-dimensional simple mixing.

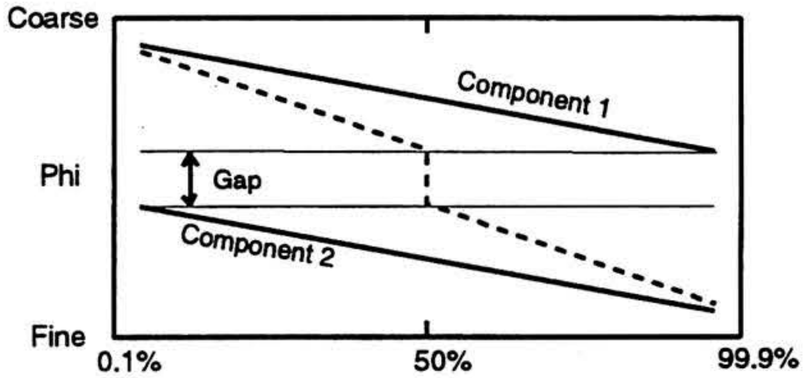


Figure 46. Two component simple mixing with disjointed component distributions.

Let us inspect the case where the components to be mixed are disjointed samples. That is, for the sake of discussion, component 1 is a Gaussian sample of particles ranging in size from baseballs to ping-pong balls, and component 2 is a Gaussian sample ranging in size from marbles to beads. Simple mixing results in a distribution illustrated in Figure 46. The vertical segment of the resulting distribution is a zero sediment segment (the gap) and contains no sediment particles.

An example of simple mixing with 3 components is illustrated in Figure 47. <u>For natural sands, 2 to 4 component mixing is common.</u>

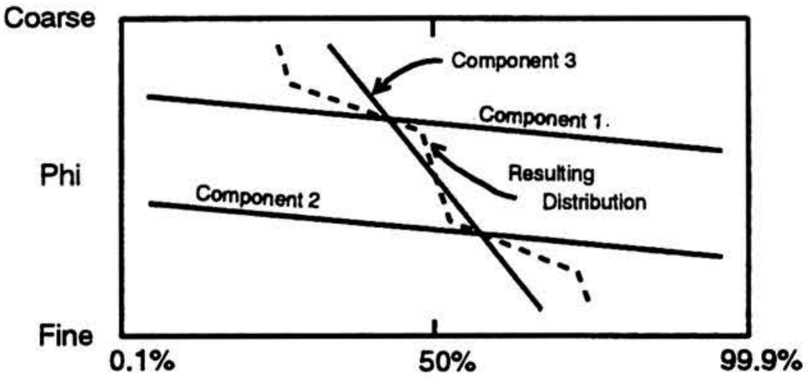


Figure 47. An example of simple three-component mixing.

Zero Component:

Sediments cannot have a zero component, since as a response element the sediment is either available or it is not present. However, it is important to realize that there are natural distributions that can have a zero component, such as ocean waves which constitute a force element that induces sedimentologic response. For instance, along the lower Gulf Coast of Florida, seas are calm for about 30% of the annual period. In fact, for beach sands, wave heights somewhere in the range of from 3 to 5 cm no longer have the competence to transport significant, if any, quantities of sand, and may be considered to be a part of the zero wave energy component. An example is illustrated by Figure 48.

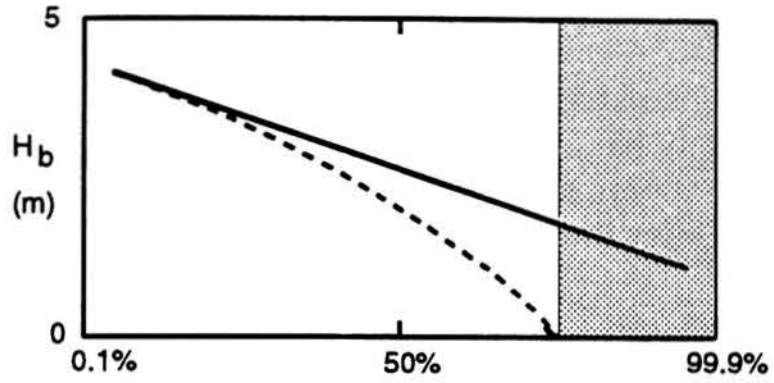


Figure 48. An example of a distribution with a zero component, in this case ocean waves.

Selection

Simple mixing is not the only way of combining components, or of distorting the distribution. Three additional methods, described as "statistical selection", are censorship, truncation, and filtering. Selection examples can be explained by laboratory procedures or by natural processes.

Censorship:

Censoring involves the suppression of all the data of one variety within a certain range of values. The missing data normally occurs in the tails of the distribution, but can occur in the central portion. There are two types of censorship.

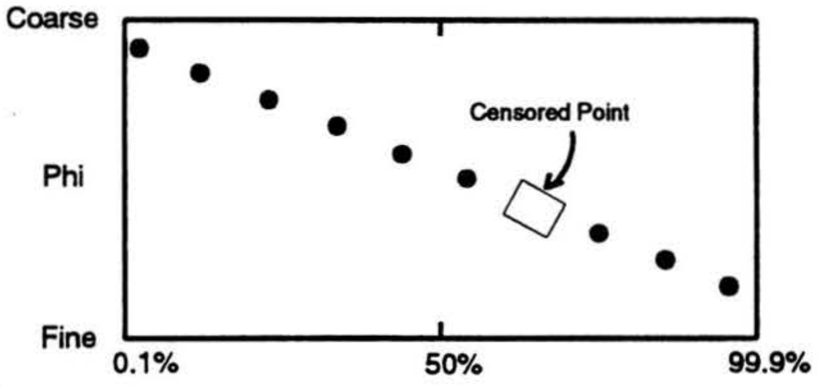


Figure 49. Example of Type I censorship .

Type I Censorship: This occurs where the number of suppressed phi size classes is known. An example is illustrated by figure 49, where one data point (i.e., one sieve) is missing. However, we know the total sample weight (which we measured prior to sieving), and the percentages for the other data points. Hence, we should be able to recover the entire characteristics of the distribution.

Type II Censorship: This occurs where the number of suppressed measurements is known, but the numerical values to be assigned to the individual items (e.g., diameters for the screens lost) are not known. For instance, the finest sieve used in the 1/4-phi interval sieve nest was 3.5 ϕ. Hence, data for the 3.75 ϕ and finer sieves are missing. However, the pan collects the total not retained by the missing sieve fractions. Again, the total weight of the sample is known, and the bulk of the weight data for the missing fractions is available.

Censorship is the mildest form of selection. In some cases, more than 50% of a sample can be missing without impeding successful analysis. In fact, many published sediment curves show simple censorship. Censorship is seldom serious because it does not generally alter the appearance of the probability curve.

Truncation:

Truncation occurs where there is a total loss of information for a number of adjacent missing 1/4-phi classes, or for a number of missing items (i.e., n number of sand grains within a 1/4-phi size class). Generally, this occurs in one or both of the tails of the distribution. The result is more serious than censorship. For instance, if we did not have the total weight of the sample before sieving and, for some reason, the pan fraction were lost, then the total weight of the sample represents only those sieves in which sediment was retained.

Truncated probability curves are difficult to handle and may require trial-and-error tessellation in order to find the original distribution (see Tanner, 1964; Appendix X, p. 139). However, one should at least be able to readily identify when truncation has occurred. It is characterized by typically smooth, gentle curves on probability paper; no inflection points occur unless some other modifications have also taken place. The truncated tail has better sorting because it plots as a flattened line compared to the rest of the curve. Either tail can be truncated to result in single truncation (see Figure 50), or both tails can simultaneously be truncated (see Figure 51).

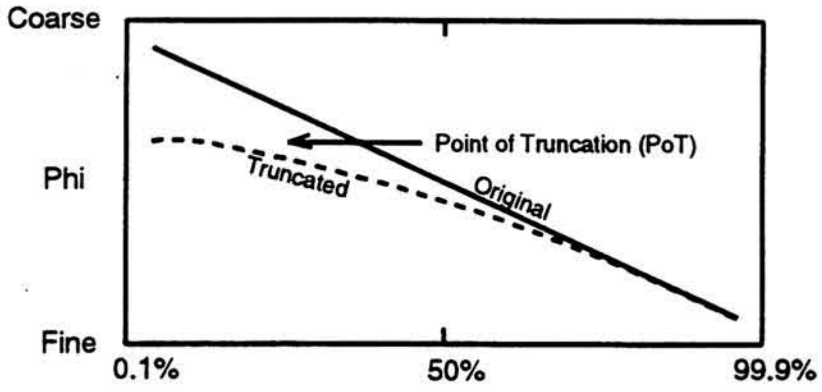


Figure 50. Example of single truncation.

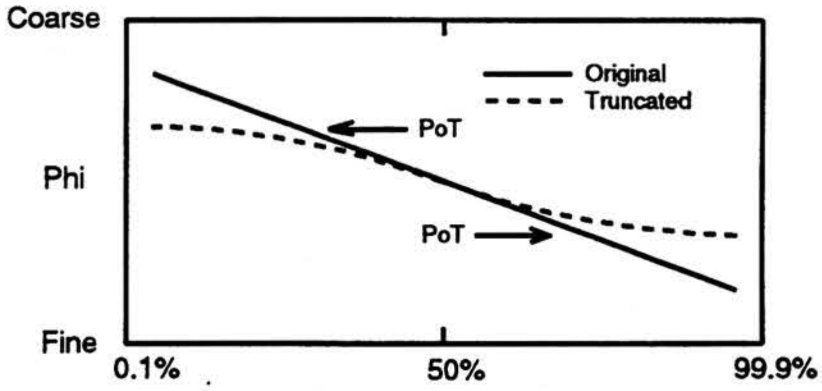


Figure 51. Example of double truncation.

Filtering:

Filtering is more problematic than either censorship or truncation. It is not relegated to a continuous segment (i.e., several sieves or size classes in numerical order), but the removal of, say, some sediment (varying amounts) from each of any number of random sieves or size classes, for which we have no quantitative information. Viewed in some ways, filtering is negative mixing, i.e., component 1 plus component 2 for mixing, component 1 minus component 2 for filtering. One might assume that the filter is Gaussian and that a negative component added to the filtered distribution will result in the original straight-line probability distribution. An example is illustrated in Figure 52, where the standard deviations of the filter and the original sample are identical. An example where the standard deviations of the filter and original distribution are unequal is illustrated by Figure 53.

There are no guidelines to correct for filtering in order to determine the original distribution. It is prudent to assume that filtering has not occurred unless there is no other explanation.

Summary

Employing Occam's Razor, the simplest procedure is probably the best procedure. A practicable endeavor might be to ignore the effects of censorship (since it does not generally alter the shape of the probability curve), to reject an hypothesis of filtering unless other evidence compels one to do so, and to distinguish through inspection of the probability curve any difference between truncation and simple mixing. The latter should not be difficult, inasmuch as the two processes normally produce quite different and distinguishable results. Once interpretive decisions have been made, the task of resolving the components can be undertaken... including the identification of points and agencies of truncation, if any.

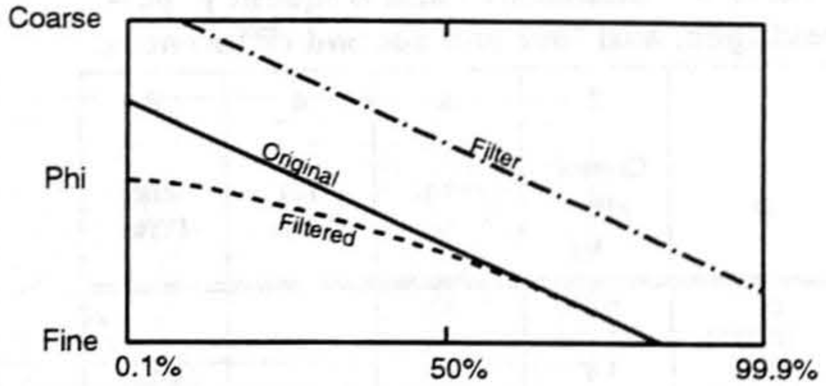


Figure 52. Example of filtering where the filter mean is coarser than the original distribution and standard deviations are equal.

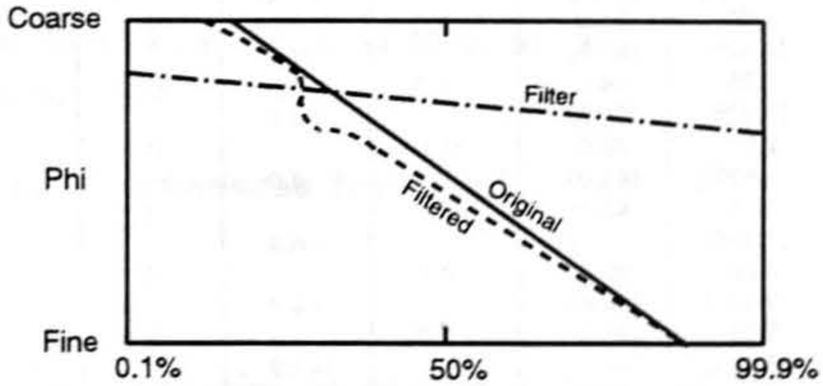


Figure 53. Example of filtering where the filter mean is coarser than the original distribution and standard deviations are unequal.

Determination of Sample Components Using the Method of Differences

The preceding section dealing with plot decomposition has demonstrated the process using, for example, simple mixing of components. In reality, however, we usually have a complete sieved sample with identificable line segments that we might wish to decompose into its constituent components. In order to do so, we can employ the Method of Differences (Tanner, 1959), which constitutes an approximation to the method of derivatives. The method is one that applies to the decomposition of any probability distribution, not just one dealing with sediments. Such work could have important implications, assisting in identifying force and response element relationships that might not otheriwse be possible to identify.

As an example, let us select an original sedimentologic distribution that is comprised

Table 9. Cumulative and frequency percentages, and first and second differences.

1	2	3	4	5
ϕ	Cumulative %	Freq. %	1st Diffs	2nd Diffs
0	0.3	0.3		
[0.125]	[0.95]		-1.0	
0.25	1.6	1.3		+1.3
[0.375]	[3.4]		-2.3	
0.5	5.2	3.6		+1.9
[0.625]	[9.1]		-4.2	
0.75	13.0	7.8		0
[0.875]	[19.0]		-4.2	
1.00	25.0	12.0		-7.2
[1.125]	[30.5]		+3.0	
1.25	36.0	9.0		+2.0
[1.375]	[40.0]		+1.0	
1.50	44.0	8.0		-1.0
[1.625]	[47.0]		+2.0	
1.75	50.0	6.0		+1.0
[1.875]	[52.5]		+1.0	
2.00	55.0	5.0		+5.0
[2.125]	[59.5]		-4.0	
2.25	64.0	9.0		-2.0
[2.375]	[69.5]		-2.0	
2.50	75.0	11.0		-1.0
[2.625]	[81.0]		-1.0	
2.75	87.0	12.0		-5.0
[2.875]	[91.0]		+4.0	
3.00	95.0	8.0		-0.7
[3.125]	[96.65]		+4.7	
3.25	98.3	3.3		+2.8
[3.375]	[99.0]		+1.9	
3.50	99.7	1.4		+0.78
[3.625]	[99.8]		+1.15	
3.75	99.95	0.25		

NOTE: Numbers in [ ] are interpolated values for plotting purposes.

of two Gaussian components (Table 9). Initially, from the cumulative probability distribution percentages (Table 9, column 2), the inner differences or frequency percentages are determined (column 3). First differences are determined from the frequency percentages and are listed in column 4. Second differences are determined from column 4 and listed in column 5.

Results of Table 9 are then plotted as in Figure 54. Important points identifying the character of the distribution and its components occur where first differences (solid line) equal zero. That is:

- Where first differences equal zero and second differences are negative, approximate means appear.

- Where first differences are zero and second differences are positive, approximate proportions appear.

Hence, Figure 54 confirms that the total or original distribution is comprised of 2 means, and 2 proportions or components. Proportions are 54% for the first component and 46% for the second. However, because of the approximating nature of this method (e.g., we are using 1/4-phi intervals), we can assume that the proportions are 1:1.

The degree of complexity involved in decomposing distributions depends on whether means, standard deviations, and proportions are equal or not. Let us look at two cases.

Case 1. Two Components with Means Unequal, Standard Deviations Equal, and Proportions Equal.

Decomposition of the original, total curve T in this case is a simple example (Figure 55) and, in fact, is here represented by the sample of Table 9 and Figure 54 (proportions assumed equal). Component A may be determined using the point plotting formula A = (2 T) - 100 where T is the upper abscissa cumulative percentile for the total (T) curve. For a given value of T (e.g., 99.5%), the resulting plotting position of A (i.e., A = (2 x 99.5) - 100 = 99%)

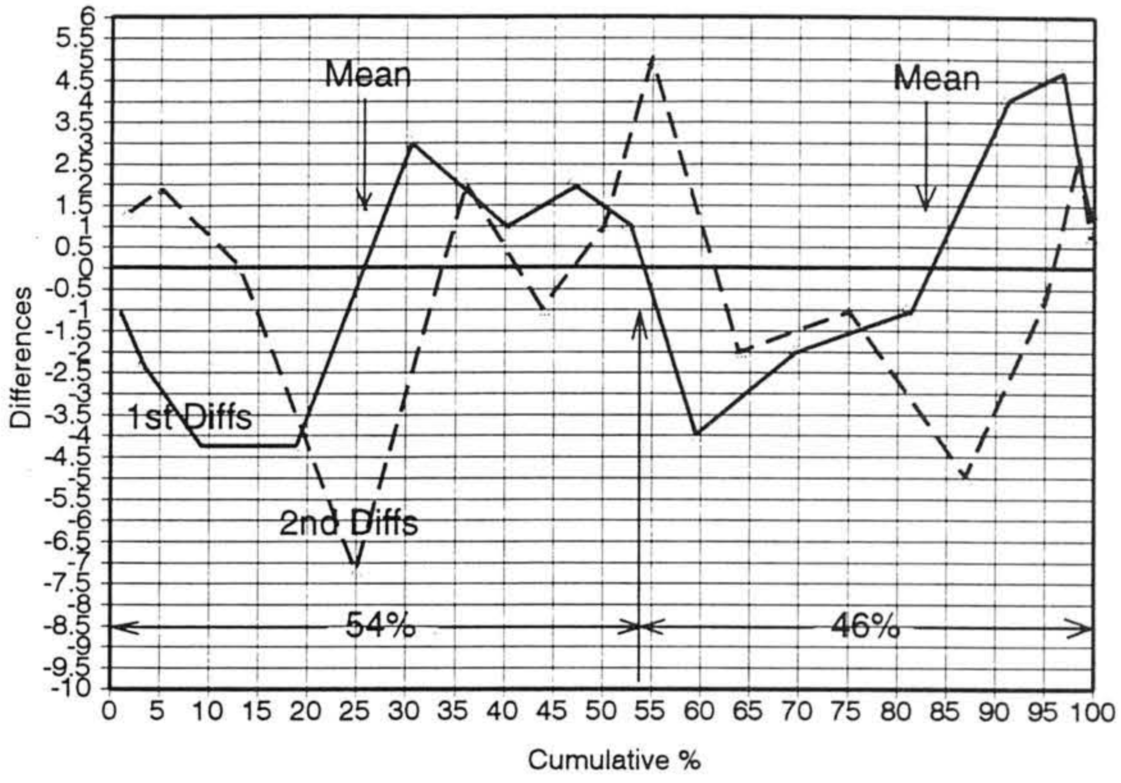


Figure 54. Plot of component 1 and 2 differences from Table 7 versus cumulative percent.

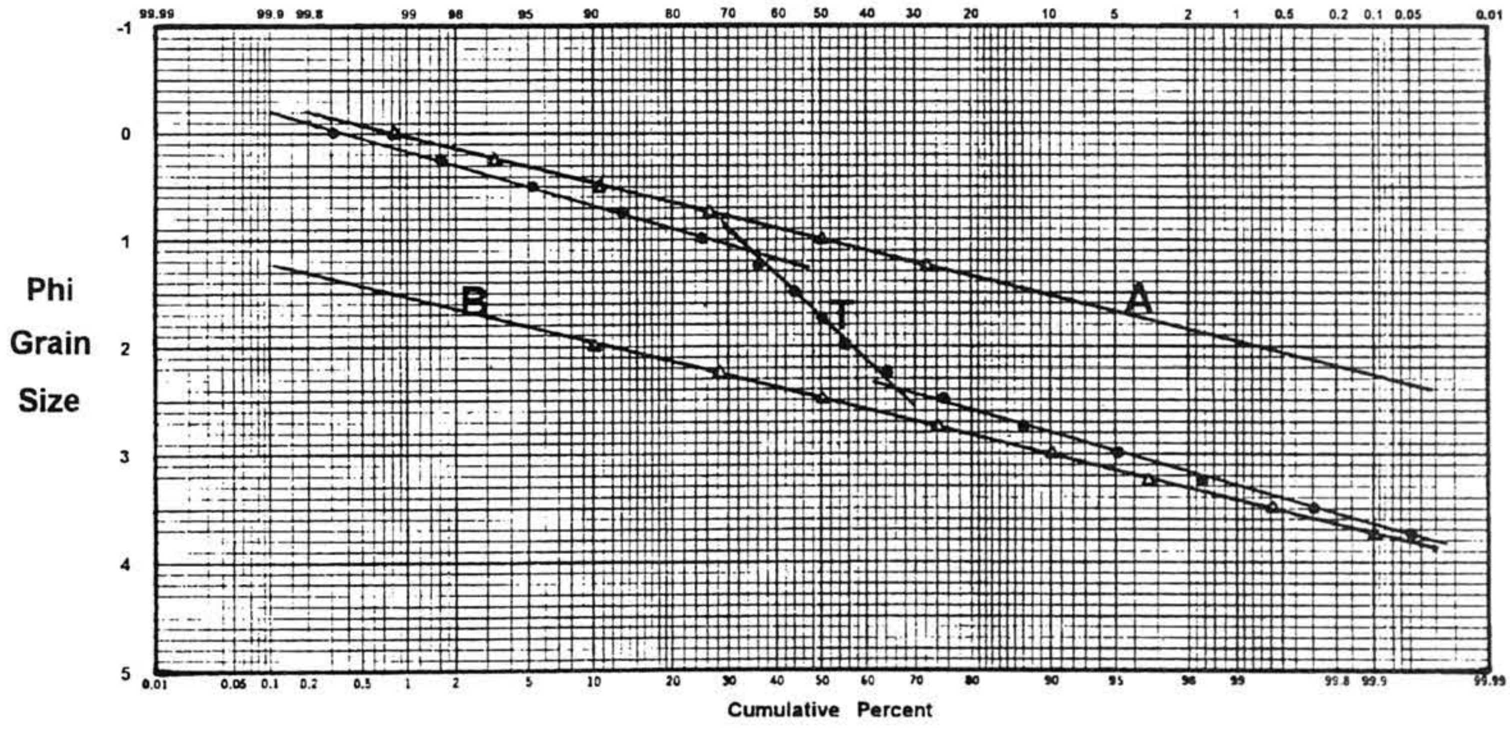


Figure 55. Case 1 original total distribution, T, and its constituent components A and B. See text for discussion.

or component A is located on the same horizontal line intersecting T = 99.5 on T. Note that negative values and values exceeding 100% have meaning, since the domain of the total curve T has been exceeded. Similarly, points for component B are identified by the point plotting formula B = (2 T) - 100. Constituent components (A and B) are plotted on Figure 55. Because the Method of Differences is an approximation, recombination of components and minor adjustments may be needed in order to locate the precise plotting position of the components.

Case 2. Two Components with Means Unequal, Standard Deviations Unequal, and Proportions Unequal.

This example is considerably more complex than case 1. The total distribution is plotted in Figure 56. Furthermore, let component A comprise 75% of the original total sample distribution, component B 25% of the distribution. The point plotting formula for the original total distribution (T) and its relationship to component A (A) and component B (B) becomes T = 0.25 A + 0.75 B or 4 T = A + 3B. It is critical that one first choose a component for which there is a recognizable solution. This might require some trial-and-error computations. Normally, however, the first component to be calculated is that which has the longest tails, and the larger slope (i.e., larger standard deviation). As shall become increasingly apparent, this assists in identifying the component which has the most percentiles for its computational

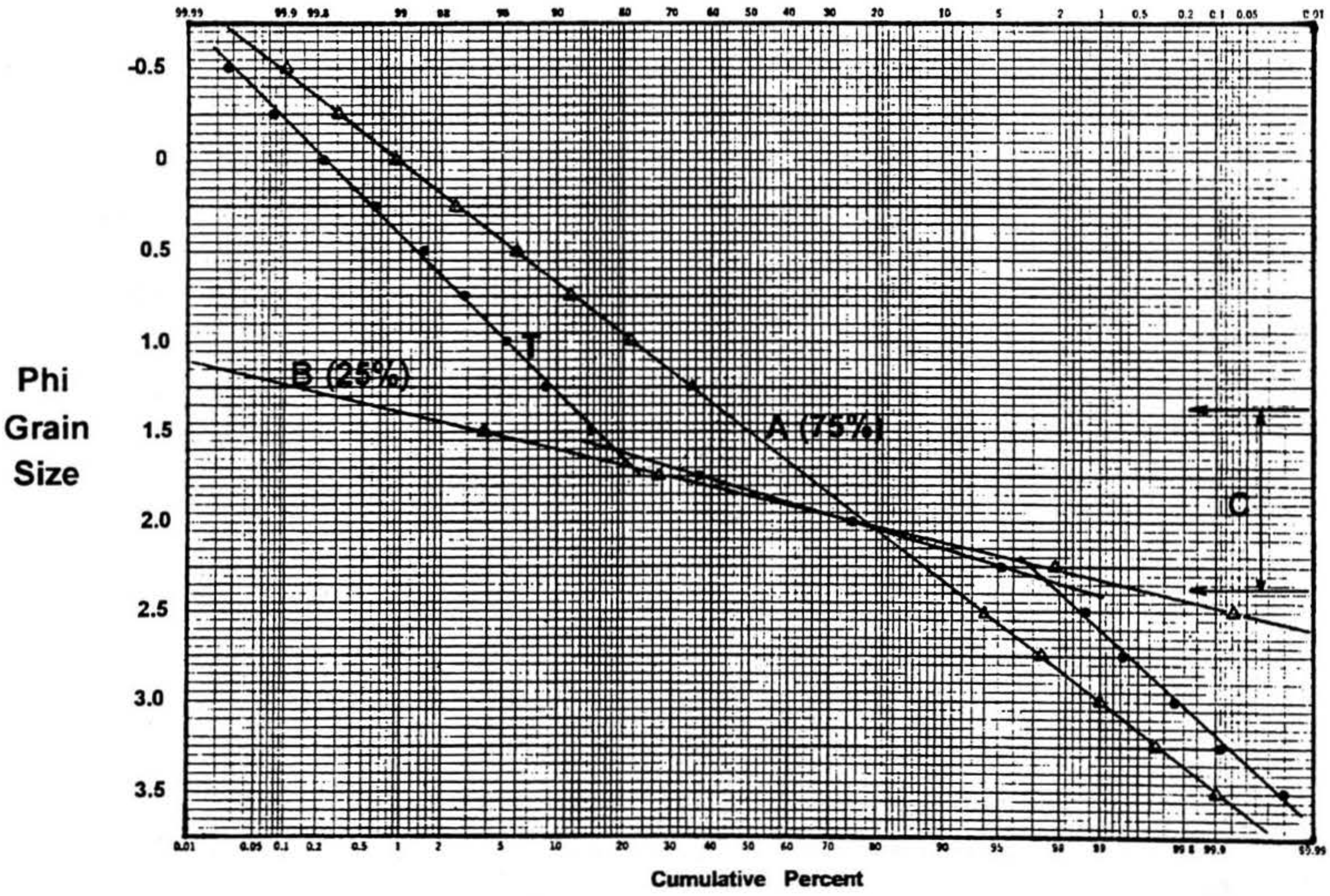


Figure 56. Case 2 original total distribution, T, and its constituent conponents A and B. See text for discussion.

definition.

Analytical results for this decomposition analysis are given in Table 10. Note that for the portion of the graph above, zone C of Figure 56, B percentiles are 100 and component A can be readily calculated since A = 4 T - 3 (100) = 4 T - 300. Similarly, below zone C, B percentiles are 0, and A = 4 T - 3 (0) = 4 T. Now, component B can be readily calculated in zone C according to the point plotting formula B = (4 T - A)/3.

Table 10. Analytical results for determination of components A and B of Figure 56.

ϕ	P [Bottom x-axis]	T [Top x-axis]	Comp A A = 4T - 3B		Comp B B = (4T - A)/3
-0.50	0.025	99.975	99.9		100
-0.25	0.075	99.925	99.7		100
0.00	0.225	99.775	99.1	A = 4T - 3B	100
0.25	0.625	99.375	97.5	where B = 100,	100
0.50	1.50	98.5	94.0	then	100
0.75	2.875	97.125	88.5	A = 4T - 300	100
1.00	5.25	94.75	79.0		100
1.25	8.58	91.42	65.68		100
1.50	14.50	85.50	50.0		96.3
1.75	36.63	63.37	36.0	0 < B < 100	72.49
2.00	75.63	24.37	22.0	Points read from	25.16
2.25	95.16	4.84	12.5	graph.	2.29
2.50	98.45	1.55	6.0		0.066
2.75	99.33	0.67	2.68	A = 4T - 3B	0
3.00	99.75	0.25	1.0	where B = 0,	0
3.25	99.91	0.09	0.36	then	0
3.50	99.975	0.025	0.1	A = 4T	0

Again, because of the approximating nature of the methodology, recombination of components and minor adjustments may be needed in order to more precisely plot positions of the components. For more involved three component decomposition examples, see Tanner (1959).

Note that numerically or physically determined components may not necessarily be Gaussian. They may be truncated, or composed of multiple line segments and, hence, contain additional components.

CARBONATES

Along both the east coast and lower Gulf coasts of Florida, the beaches are comprised of significant amounts of calcium carbonate ($CaCO_3$) sediments, primarily shell hash. Such deposits are charcteristically variable, and highly so. That is, in one locality it might be 99% quartz, and in another 99% calcium carbonate. When pursuing the collection of quartzose samples, even for the informed perhaps the best one can do, is take a sample containing 20

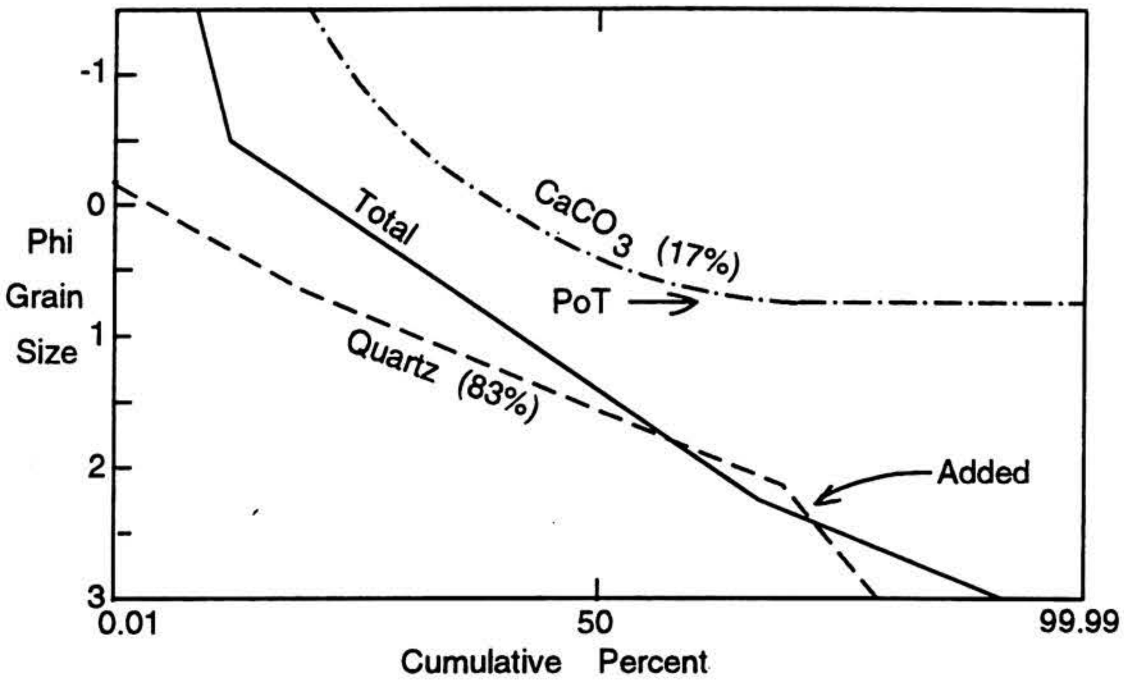


Figure 57. Beach sample from Sanibel Island, Florida, containing a calcium carbonate shell fraction. Components were physically determined using HCl. PoT designates the point of truncation. See text for discussion.

to 30% $CaCO_3$. Suppose that such a sample (50 to 100 grams) is taken on Sanibel Island located along the lower Gulf Coast, such as one collected by Neale (1980). The sieved results are plotted in Figure 57. Following sieving of the total sample (solid line in Figure 57), we then digest the $CaCO_3$ using HCl and re-sieve the mostly quartz insoluble residue. The resulting distribution (83% of the total sample) is given by the dashed line of Figure 57. By numerically subtracting the insoluble residue (mostly quartz) distribution from the originally sieved distribution, the $CaCO_3$ distribution (17% of the total sample) is determined (dash-dot-dash line of Figure 57). The shape of the originally sieved distribution should provide a clue that the $CaCO_3$ component is truncated. But, what of the two-segment quartz (insoluble) distribution (dashed line)? In fact, the line segment labelled as "added" represents insolubles appropriated by organisms and contained within the shell matrix, that were released due to HCl digestion. Hence, these insoluble particles are not represented by the total curve, since they were hidden, or filtered (see Tanner, 1964; Appendix X, p. 139).

Let us look at some other differences between quartz and calcium carbonate. In terms of Mohs hardness scale, calcium carbonate is 4 orders of magnitude softer than quartz. Hence, where quartz and carbonate mixtures occur, the quartz will accelerate abrasion of the softer material. Just how fast this occurs is not known, but should be especially accelerated during periods of higher energy, such as during storm impacts.

Mass densities of both quartz and calcium carbonate vary slightly, depending upon impurities present. They are, however, quite similar in value.

In terms of chemical stability, calcium carbonate is 8 to 10 orders of magnitude chemically less stable than quartz. Rainfall, runoff, and high tide waters will probably dissolve $CaCO_3$ in upper layers of the foreshore and beach, and precipitate at lower elevations in the sediment column. How much lower in elevation? Not much. Beach rock that is well developed in beaches of Florida, attests to the highly mobile mature of $CaCO_3$, in terms of its ability to be dissolved and re-precipitated. In southeast coastal Florida there are anthropic materials cemented within beach rock, such as Coke bottle fragments and automobile parts. Automobile parts certainly were not available in any quantity prior to about 1925. Such cementation, therefore, requires less than 70 years. How much less is unknown.

Carbonate material has much more variability in shape than quartz. Mostly, $CaCO_3$ is plate or rod shaped, while quartz particles are nearly equidimensional. In the company of one another the plate-shaped particles significantly change the hydrodynamic response of the quartz particles. Platy particles exhibit significant lateral movement when settling in water. Consequently, the grain-size distribution is seriously impacted and becomes "warped" in some way which cannot be analyzed.

Should we, therefore, forget about carbonates, and focus attention on the quartz fraction only? Currently, we do not know with certainty what percent of the nearshore sand pool is carbonate. At the very least, we need such measurements.

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NOTES

Appendix I

Socci, A., and Tanner, W. F., 1980, Little known but important papers on grain-size analysis: Sedimentology, v. 27, p. 231-232.

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Sedimentology (1980) 27, 231-232

SHORT COMMUNICATION

Little known but important papers on grain-size analysis

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ABSTRACT

Some important papers have apparently gone unnoticed by most sedimentologists, as shown by their absence from bibliographies of recent texts. These papers concern sample size, permissible number of splits, sieving time, and sieve-*vs*-settling tube comparisons. These papers were published where sedimentologists would not ordinarily see them, but should be required reading for students.

The recent appearance of two encyclopaedic works on sedimentology (Friedman & Sanders, 1978; Fairbridge & Bourgeois, 1978) having unusually complete bibliographic references, provides an opportunity to check the state of the art and to identify significant gaps in the coverage provided. This is important because these two books probably will serve as the 'core storage' for sedimentological knowledge for some years to come.

We would like, therefore, to draw attention to several key papers in sedimentology which we have been unable to find referenced in Friedman & Sanders (1978), Fairbridge & Bourgeois (1978), Selley (1976), Pettijohn (1975), Pettijohn, Potter & Siever (1972), Carver (1971), Blatt, Middleton & Murray (1972), Folk (1974), Berthois (1975), Griffiths (1967), and Tickell (1965).

For example, a classic paper by Mizutani (1963) on sieving methodology was one of the compelling reasons for insistence, some years ago, that scientific work in the Florida State University laboratories be carried out to new standards: quarter phi sieves, 30 min sieving time, and relatively small initial sample (40–50 g, after no more than one split). The most practical aspect of Mizutani's paper, in our opinion, has to do with sieving time (although he addressed a more important question than this).

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De Vries (1970) considered the problem of sample size. In a graph (p. 530) de Vries showed a plot of representative grain size *vs* sample size, with index lines for 'high accuracy', 'normal accuracy', and 'low accuracy'. For example, for D_{84} sand of 0·5 mm diameter (84% of the sample is finer than 0·5 mm), the high accuracy line indicates that the sample size should be about 25 g. This important paper likewise is not cited in any of the works mentioned above.

Emmerling & Tanner (1974) showed that a suitably small sample cannot be obtained by repeated splitting, without introducing a devastating (compounded) splitting error, and they recommended a single split only. This suggests that the original sample be not more than 60–100 g (or, in rare cases, where two successive splits must be taken, regardless of the error introduced, 120–200 g).

Coleman & Entsminger (1977), in a comparative study of sieving, settling tube work, and grain measurement under the microscope, showed that there are important differences between sieve and settling tube data, only one of which is that the latter are not as accurate as the former (verification under the microscope) as a measure of grain size.

We would like to emphasize that our intention in writing this note is not to criticize current texts, but to draw attention to important papers, in publications not commonly read by sedimentologists. We are aware of the almost impossible task of keeping abreast of the ever-increasing volume of geological information, even within one's own area of specialization.

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NOTES

Appendix II

Guidelines for Collecting Sand Samples

Guidelines for Collecting Sand Samples

Items 1 through 14 of this list apply to sampling of beach ridge features. Items 7 through 14 (depending upon the feature) apply to dunes, subaerial beaches, etc. Subaqueous sampling requires specialized considerations.

1. Do not work at the map ends of beach ridges (map sense); stay reasonably close to the middle (map sense). Hydrodynamic influences are too complicated at (or near) ends or tips.

2. For multiple ridges, the numbering scheme should start with the oldest ridge (Sample No. 1), and finish with the youngest. However, it is commonly advisable (for various reasons) to start work with the youngest ridge; in this case, use Number 200 for the youngest sample, then 199, then 198, etc. In this scheme, the oldest sample may turn out to be #153, or something like that. This permits Little Ice Age ridges to be sampled, in case the profile cannot be finished, or the number of ridges is small, or older ridges are problematical (the younger ridges are generally easy to identify; they give a time interval between ridges, hence tentative dates for the entire system).

3. Measure or pace, and record, distances between samples (ridges). Use this distance when uncertain about the presence or absence of a subtle ridge.

4. Collect from the seaward face.

5. Select a site halfway (vertically) between crest and swale.

6. Avoid eolian hummocks, if there are any, by moving parallel with the crest, maintaining the half-way position.

7. Dig to a depth of about 30-40 cm.

8. Use a spatula to collect a laminar sample, or nearly-laminar sample. If bedding is not visible, then <u>assume</u> that it was parallel with the ridge face.

9. Measure the sample, in a calibrated measuring cup, as follows:

   a. If one split <u>MUST</u> be made later: 90 - 100 grams.

   b. For transport by air (no split): 45 - 50 grams.

Calibration of the measuring cup must be done in advance, using dry quartz sand.

10. Remove twigs, roots, leaves and other extraneous matter.

11. Place in plastic zip-loc bag (heavy duty); put sample number on high-adhesion masking tape, on outside of the bag. Do not put paper inside bag; it tends to get wet. Do not use ink or crayon on outside; it rubs off. Make sure the bag is locked tightly.

12. Clean cup thoroughly after collecting each sample. No single grain of sand, from one sample, should be allowed to contaminate the grain-size distribution of the next sample.

13. Mark the beginning and end of the traverse on a topographic or other suitable map. Place sample numbers, where appropriate, next to key features such as the junction of dirt roads or trails.

14. Note the height of crest (above adjacent swales), front slope angle, map distance between crests, and other pertinent information (such as extent of eolian decoration, if any).

If only one ridge is to be sampled, (e.g., there is only one ridge present, or one ridge warrants detailed study), then multiple samples might be taken on the face of a cut (trench) at right angles to the crest, in a horizontal line about half-way down from the crest. If no trench can be dug, samples can be collected at regular intervals (such as 5 or 10 or 20 m), on the seaward face, about half-way down from the crest, in a line parallel with the crest. In any event, sample locations should be sketched (map sense).

Revised 28 April 1994 W. F. Tanner

NOTES

Appendix III

Laboratory Analysis of Sand Samples

Laboratory Analysis of Sand Samples

In North America sieve nests are everywhere standardized and comprised of half-height U. S. Standard sieves, 8 inches in diameter.

The initial sample should be 45-60 grams. If it is 80-120 grams, it can be split once. A second split should not be made; samples larger than 120 grams are too large for useful work, because they require more than one split and thus introduce a compound splitting error.

The initial sample should be very fine gravel, sand, and coarse silt (and perhaps a small amount of clay), but nothing coarser, and nothing finer. It should be clean and free of plant debris and /or shell fragments (of any size). Shell fragments can be removed with hydrochloric acid; after treatment and washing, the residue should be 45-50 grams. Hydrogen peroxide can be used to remove fine organic matter.

If some clay is present, it should be in dispersed form, but not in flocs, clumps, or blocks. If it is not in dispersed form, then it should be treated with Calgon, or Varsol, and/or ultra-sound. Normally, clay and/or very fine silt, up to about 15-20% of the total, can be handled, more or less satisfactorily, in the sieving process. However, one gets more accurate results by separating the clay-and-fine-silt fraction and then measuring it in the settling tube. In this case, the sand fraction (down to 4.5 phi) can be analyzed by itself (clean sand). The data on the silt-and-fine-clay must not be discarded.

The best procedure for measuring the sand grain size is sieving. Counting grains on a microscope slide is extremely slow and tedious, and produces unknown operator error; it is probable that it is not replicable. The settling tube displaces the mean significantly, minimizes polymodality, reduces the numerical value of the standard deviation, and distorts the higher moment measures, in many cases severely; this is because the settling tube adds a particular hydrodynamic character (due to grain-to-grain interactions which modify greatly the settling velocities of individual particles) which was not present in the original sample.

There are several other techniques for measuring grain size, but some of them do not cover the necessary size range in acceptable fashion, and others have not been calibrated properly yet.

Sieving should be done in 8-inch-diameter, half-height, steel-screen sieves having a quarter-phi interval, and should use 30 minutes per sample on a mechanical shaker. Weighing may be good enough to 0.001 gram, but if the balance is capable of doing so, 0.0001 is better (for later rounding off). The weight prior to sieving should be compared with the total of the size-fraction weights, to determine the magnitude of error in sieving; sieve loss is, ideally, no more than 0.1 - 0.5 percent (about 10 to the negative 3).

The raw weights that are obtained in this fashion are suitable for advanced statistical analysis, using the first six moment measures (GRAN-7 computer program). These parameters can be evaluated for the entire sample suite, provided that it is homogeneous (using the SUITES program). If the samples were taken along an historical line (e.g., from oldest to youngest), individual parameters can be smoothed slightly (moving averages; window = 5, 7 or 9), to produce a history of depositional conditions.

Cf. Socci and Tanner, 1980. In: "Sedimentology", v. 7, p. 231.

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Appendix IV

Example Calculation of Moments and Moment Measures for Classified Data

Example Calculation of Moments and Moments Measures for Classified Data (After Fogiel, et al. 1978)

Class	Frequency f_i	Mid-Point X_i	Mean $\bar{X}$	Mean Deviation $(X_i - \bar{X})$	$f_i (X_i - \bar{X})^2$	$f_i (X_i - \bar{X})^3$	$f_i (X_i - \bar{X})^4$
49-54	6	51.5	66.5	-15	6(225)=1350	-20250	303750
55-60	15	57.5	66.5	-9	15(81)=1215	-10935	98415
61-66	24	63.5	66.5	-3	24(9)=216	-648	1943
67-72	33	69.5	66.5	3	33(9)=297	891	2673
73-78	22	75.5	66.5	9	22(81)=1782	16038	144342
Totals	100				4860	-14904	551124

It is now possible to compute the moments and the moment measures, where $n = \Sigma f_i$. The **first moment** is the average or mean, m_1, given by:

$$m_1 = \frac{\sum f_i X_i}{n} = \frac{6(51.5) + 15(57.5) + 24(63.5) + 33(69.5) + 22(75.5)}{100} = 66.5$$

which is also the **first moment measure**(which can have units).

The **second moment,** m_2, is calculated according to:

$$m_2 = \frac{\sum f_i (X_i - \bar{X})^2}{n - 1} = \frac{4860}{99} = 49.09$$

which may have dimensions of units squared, and the **second moment measure** or **standard deviation** (or sorting coefficient), σ, is:

$$\sigma = \sqrt{m_2} = \sqrt{49.09} = 7.006$$

with possible unit dimensions.

The **third moment,** m_3, is determined as:

$$m_3 = \frac{\sum f_i (X_i - \bar{X})^3}{n - 1} = \frac{-14904}{99} = -150.55$$

and is always dimensionless. The **third moment measure,** termed the skewness, Sk, is also dimensionless and is given by:

$$Sk = \frac{m_3}{(m_2)^{1.5}} = \frac{-150.55}{49.09^{1.5}} = \frac{-150.55}{343.95} = -0.438$$

The **fourth moment**, m_4, is produced by:

$$m_4 = \frac{\sum f_1 (X_i - \bar{X})^4}{n - 1} = \frac{551124}{99} = 5566.91$$

and is dimensionless. The **fourth moment measure**, called the **kurtosis**, K, a dimensionless parameter, is determined by:

$$K = \frac{m_4}{(m_2)^2} = \frac{5566.91}{49.09^2} = \frac{5566.91}{2409.83} = 2.31$$

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Appendix V

Tanner, W. F., 1994, The Darss: Coastal Research, v. 11, no. 3, p. 3-6.

Coastal Research

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The Darss

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Abstract

Beach ridges on the Darss (Baltic coast, Germany) are in good part masked by eolian sand, but nevertheless show clear evidence that they were formed under low-to-moderate-energy swash on a fair-weather beach. This is indicated by granulometry of 16 samples from trenches; suite analysis methodology makes the distinction easily. Probability plots show many examples of the "surf break," but not the "eolian hump," and each of these is fully diagnostic. Therefore the ridges have only minor eolian content, primarily in the form of a wind-worked cover.

Many workers, without trenching, identified the ridges as dunes, because of surface geometry. Ul'st (1957) reported low-angle fair-weather beach-type cross-bedding, but his work has been ignored or rejected.

Even though the origin is clear, the number of ridges is very difficult to ascertain, because of the eolian veneer.

Introduction

This brief preliminary report treats the ridge system on the Darss, on the Baltic coast northeast of Rostock, and northwest of Stralsund, Germany. This system has been described by various authors as made up of beach ridges, dunes, dune ridges, or foredunes (cf. Kolp 1982). Most authors have chosen "dunes."

Johnson (1919 p.427) in a photo caption called them "forested dune ridges" (linear dunes). Schütze (1939) followed earlier writers, who had assumed that they are dunes. Fukarek (1961) quoted Hurtig (1954, 1957) to the effect that the ridges were built of sand from offshore sand-banks; this is not a definitive statement about immediate origin. Zenkovich (1967 p. 295, 609-612) labelled them as dunes; although he cited Ul'st (1957) showing beach-type cross-bedding, he rejected that idea, and chose an eolian origin. Lobeck (1939 p. 356) identified them, correctly, as dune-covered beach ridges.

Although Ul'st (1957) labelled the alignments on the Darss as "dunes" (because they look like dunes; brief caption, p. 161), he also commented in more detail that they are beach ridges with a covering of eolian sand (p. 160). Eolian deposits on top of swash-built beach ridges are common in many places, and the wind-blown sand tends to accumulate on the ridge crests, but irregular eolian topography is not a clue to ridge origin.

Harald Elsner (personal comm., 1993) inspected the area and described the

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eolian influence as pervasive. He collected 16 sand samples, using standardized field procedure (requiring trenching).

Those samples have been analyzed, using "suite statistics" methods (Tanner 1991-a, 1991-b). As is true in other places, wind work was not as effective as had been thought. The fact that pre-dune samples were obtained is due to the practice of avoiding obvious eolian features, and taking no surface sand, but digging to a depth of some 30-50 cm for each sample.

That is done because much so-called dune deposition in beach ridge systems is in fact only a veneer of eolian sand on top. Furthermore, modest reworking by wind commonly does not change beach grain size distributions to eolian ones. It takes a good deal of transport to erase all the granulometric characteristics of the mature beach, and to impart the characteristics of wind work.

Granulometry

Data from six Darss sand samples (No. 135, 144, 145, 147, 149, 150) are summarized below. This list is based on hand plotting of suite parameters, two at a time, against well-known number fields (Tanner 1991-a, 1991-b):

i. Fluvial:	Not one sample.
ii. Dune or eolian:	2 plots.
iii. Swash:	5 plots.
iv. Settling (from water):	7 plots.

The "fluvial" class must be eliminated (no river samples; also, no river).

"Suite statistics" methodology identifies the beach setting, without ambiguity, and also shows that the wave energy level was "low to moderate" (not "high"). Therefore there was swash action, due to low-to-moderate-energy waves, plus a settling component (perhaps the mechanism of Postma; Tanner and Demirpolat, 1988). Wind was not the primary depositional agency, but reworked a thin veneer of sand at a later date.

The swash-plus-settling combination is rather common on low-to-moderate energy beaches. It has been seen in a variety of other places, including Mesa del Gavilán (near Boca Chica, east of Brownsville, Texas, U.S.A.; Tanner and Demirpolat, 1988), the Jerup-Tversted low-energy ridge systems in extreme northern Denmark (Tanner 1992-a, 1992-b, 1993-a), and the cheniers of southwestern Louisiana (U.S.A.; Tanner 1993-b).

Grain-size probability plots of these six samples show two distributions which are almost perfectly Gaussian, two good examples of the "surf break" (low-to-moderate-energy swash; Tanner 1966), one example of a distinctive coarse tail which may indicate glacial debris in the area, and one problematical example, but not a single "eolian hump" (wind evidence).

Analysis of eleven of Elsner's samples (the previous six plus Numbers 160, 170, 187, 189 and 190) yielded the following:

i. Settling (water): five plots.
ii. Beach: five.
iii. Dune: two.
iv. River: none.

This means low-to-moderate-energy fair weather swash, and settling from water.

The mean of the kurtosis, versus the standard deviation of the kurtosis, places these 11 samples with the Jerup (Denmark) beach ridge sands, where the beach-plus-settling interpretation is clear (154 samples). On the various cross-plots, the Darss samples are not located near known continental-interior dunes, but might resemble, in some minor way, coastal dune sands with a previous beach history. Probability plots of individual sand samples show the "surf break," but not the "eolian hump."

The entire suite (16 samples) has 12 examples of the "surf break," only minor-to-negligible evidence for wind work, and not a single "eolian hump." The entire suite indicates swash work and settling, on a low-to-moderate-wave-energy beach.

Specifically, the cross-plot of kurtosis vs standard deviation (n = 16) shows a combination of swash-and-backwash, and settling from water, and matches rather closely similar beach ridges from Mesa del Gavilán, Texas, and from the Tversted-Jerup area (Denmark). The cross-plot of mean-of-kurtosis vs standard-deviation-of-kurtosis also places the Darss samples with the Mesa del Gavilán examples and with the Tversted-Jerup beach ridges.

Therefore, this analysis shows that the Darss sands represent essentially the same beach environment as the Tversted-Jerup samples, even though later wind work was surficially extensive in the Darss area. This analysis also indicates that the field impression of pervasive wind influence must not be extrapolated to depth; these sand samples represent swash-built fair-weather beach ridges, but not dunes, and the granulometric data match the cross-bedding described by Ul'st. Hence Elsner's trench samples provide reliable information.

The surface of the Darss beach ridge plain has been modified a great deal by later wind work, as shown by many published misidentifications of the ridges. Later wind influence makes sampling difficult, if one wishes to get swash-built beach-ridge sand samples; therefore it will be impossible to collect a complete, reliable set of samples, ridge by ridge, if one wishes to derive a detailed sea-level history, without extensive digging (Tanner 1992-a).

Number of Ridges

The ridges are hard to count, because of the dune cover. Schütze (1939) summarized earlier work, cited counts from 121 ridges to 180-plus, and tried to use historical data to determine rate of growth. He adopted a figure of 35 years per ridge (the Brückner cycle), which yields 4135 years for 121 ridges, or 6300 years for 180 ridges; he also used other numbers, obtaining younger dates (2800-3000 B.P.).

If the Darss ridges are like those in the Jerup-Tversted area, then perhaps timing from Denmark can be transferred to the Darss. If so, the Darss ridge system appears to have started about 3,200 years ago, leading to the following inferences:

If 121 ridges, then	26.4 yrs each
150	21.3
173	18.5
180	17.8
200	16.0

The first, second and fifth do not match any known periodicity in any other well-studied sandy beach ridge system. The third is close to the periodicity of a beach ridge plain on the Pacific coast of Mexico (Nayarit and Sinaloa; 18.6 years). (Average periodicity in the Jerup system (Denmark) and the St. Vincent Island system (Florida) was 50-51 years.)

Each swash-built beach ridge was made during, and because of, a sea level rise-and-drop pair, with a magnitude of 5-30 cm (Tanner 1992-b). Various studies have produced different time intervals for beach ridges, ranging from as little as 3-4 years (Tanner 1990), to 1,000 years or more. This is possible because several different periods are available on the coast (e.g., the El Niño-Southern Oscillation, at 3-7 years, plus many other longer periods). It appears that the local availability of new sand selects the period that will be used, with large availability creating short map spacing and short time intervals.

A transverse line (right angles to ridge crests), at the widest part of the Darss system, was measured on a map to be 5360 m long. If the ridge counts, used above, are employed, one can calculate average map spacing between ridges. This spacing, with time intervals listed above, produces an accretion rate as follows (m/yr):

If 121 ridges, then	44 m and	1.67 m/yr
150	35.7	1.67
173	31	1.67
180	30	1.68
200	27	1.69

This is higher than a "typical" value (roughly 1.0 m/yr), but is not excessive. Perhaps 120-173 ridges is about right.

Wind Work

Rizk (1991) studied the wide beach ridge system on St. Joseph Peninsula (Florida, U.S.A.). His study area includes numerous swash-built beach ridges, many of which are covered locally by dunes. He trenched several dunes and underlying ridges, studied the bedding, and collected numerous samples. Granulometric analysis produced the same results as his cross-bedding study. He was able to state, with great precision, which part of each trench wall represented swash work, and which was eolian. The critical parts of his work were trenching and granulometric analysis.

Chaki (1974) studied swash-built, but wind-modified, beach ridges on Cape Canaveral (Florida, U.S.A.), trenching to 30-50 cm for samples. She showed that it is relatively easy to get beach-type sand samples. Various other publications (e.g., Johnson, 1919) which identify the Cape Canaveral ridges as dunes, were based on surface inspection only, with no trenching and no granulometric work.

Certain famous beach ridge plains (the Darss; Cape Canaveral) are not as easy to study as some less-well known ones (e.g., Tversted and Jerup systems, Denmark). This is largely because of extensive dune decoration and eolian reworking which modifies the surfaces of many swash-built ridges. However, preliminary results from the Darss, reported here, indicate once more that dune-decoration is not an insuperable problem, although it makes sample collecting difficult.

Conclusions

Many people have identified ridges on the Darss (German Baltic coast) as wind-built dunes. A previous worker who dug trenches (Ul'st 1957), reported fair-weather beach-type cross-bedding, but this finding has been largely ignored or rejected.

Sand samples, from trenches on the Darss, show clearly that the underlying ridges were built under fair-weather conditions by low-to-moderate-energy swash, plus settling from water. This is in agreement with the findings of Ul'st. The present conclusion, based on granulometric parameters of sand samples taken from trenches, is strongly supported by the facts that the suite of 16 samples shows many examples of the "surf break" on probability plots, not a single example of the "eolian hump." Each one of these kinks is fully diagnostic.

It is clear that extrapolation of wind work, from surface dunes, downward into underlying beach ridges, was a mistake. The critical information is obtained by trenching. The ridges were built by fair-weather low-to-moderate-energy swash, in combination with settling from water. Eolian decoration was added at a later date.

Acknowledgement

Appreciation is hereby expressed to Dr. Harald Elsner, who carried out the reconnaissance on which this report is based.

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Table I

Means, standard deviations and relative dispersions (16 samples; phi measure except where noted):

Mean Diameter	2.148 (0.226 mm)	0.088	0.041
Std.Deviation	0.311	0.044	0.142
Skewness (3rd)	1.343	0.690	0.514
Kurtosis (4th)	12.989	4.929	0.379
5th Moment Measure	91.331	45.045	0.493
6th Monent Measure	845.479	425.515	0.503
Tail of Fines	0.0021	0.0022	1.050

The third column shows (small numbers) that the mean and standard deviation are the least variable of these parameters, and the kurtosis is next best, but all six of the moment measures are reliable.

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Appendix VI

Tanner, W. F., 1990, Origin of barrier islands on sandy coasts: Transactions of the Gulf Coast Association of Geological Societies, v. 40, p. 819-823.

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ORIGIN OF BARRIER ISLANDS ON SANDY COASTS

William F. Tanner[1]

ABSTRACT

Most theories on the origin of sandy barrier islands are statements that they migrated to the positions where they are now observed. These theories do not explain origins, but only displacements. Many sand barriers were clearly not the product of displacement, hence we need an explanation for birth in situ. Theories based on drowning do not apply to many sandy barriers.

A small sea level drop (e.g., a few feet) would be ample to convert a suitable shoal to a stable sub-aerial island. If there were an abundant nearby supply of sand, this island nucleus would then expand in area.

Several such small sea level drops are now known from middle-to-late Holocene time. Many sandy barrier islands in the study areas date from shortly after the mean sea level high at 2,500-2,800 B.P. A few are earlier than 3,000 B.P., a few are later than 1,500. But island nuclei are relatively common on wide barriers that formed more recently than 3,000 B.P.

BACKGROUND

How do sandy barrier islands form, in settings where such islands did not exist previously? Many authors have offered hypotheses. King (1972) provided a summary, including the following items:

1. de Beaumont (1845). Build-up by landward movement of offshore matter.
2. Gilbert (1890). Build-up by spit growth, then later segmentation.
3. Hoyt and Henry (1967). Mass migration in a shore-parallel direction.
4. Leontyev and Nikiforov (1966). Vertical accretion on submarine bars.
5. Hoyt (1967). Drowning of mainland dunes.
6. Fisher (1968). Modification of pre-existing spits.
7. Otvos (1970), Upward growth of offshore shoals.
8. Shepard (1963). Slowing rate of sea level rise.
9. W. P. Dillon (1970). Landward migration of a pre-existing island.

In this list, Nos. 2, 3, 6 and 9 undertake to explain how an island came to be located at a specific map position as a result of lateral translation of some kind, but do not explain how an island can be initiated at a stated position in the first place.

Nos. 4 and 7 are almost the same, the primary difference being the choice of pre-island geometry (whether a bar or a shoal). The remaining items are:

1. Landward movement of offshore material.
4, 7. Vertical build-up, in place, by offshore material.
5. Drowning of mainland dunes.
8. Slowing of the rate of sea-level rise.

No. 8 is a statement that when sea level rise slows down, barrier islands are then built. But this provides very little, if any, explanation of what happens. In No. 1 there is no explanation of how it is that the migrating sediment becomes concentrated at one locality, if not immediately adjacent to a pre-existing beach, thus forming a new island. And Nos. 4 and 7 are not concerned with the problem of converting a sub-aqueous sediment mass into a sub-aerial island, a process which certainly has not been conspicuous in forming islands in the last few centuries. Finally, No. 5 includes the hypothesis of drowning, in order to provide for a significant amount of water landward of the new island, and to permit the pre-existing sediment body to protrude above that water surface, but it does not appear to apply to very many sandy barrier islands.

Fisher (1982) reviewed the problem, and mentioned — along with some of the others cited above — the following:

10. Merrill (1890). Raising the sea floor to convert a bar to an island.
11. McGee (1890). Drowning of mainland coastal ridges.

No. 10 is epeirogenetic, but could be replaced by a sea level drop. No. 11 is a clear statement of the idea popularized later by Hoyt (1967).

Evans (1942), along with many others, felt that no submerged bar or shoal could be built above water level, because in due time a depth is reached at which wave action would keep the shoal (or bar) surface scoured clean, and there would be no further upward growth. He was probably right, provided water level did not ever change significantly.

In writing his summary, Fisher (1982) opted for multiple hypotheses, and included a table giving 10 choices. This table lists major proponent, geographic region of occurence, sediment source and primary mechanism. Under the heading "Primary Mechanism," Fisher used, at six places, words such as emergence, submergence and transgression (that is, drowning).

It is hard to see how sea level rise (drowning) can create an island, except by submerging — incompletely — a pre-existing feature. This concept may well have become popular

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because island initiation has generally been assumed to have taken place during, or at the end of, Holocene sea level rise. That is, the facts show that a rise took place, so the hypothesis must be correct. This simplistic view contains at least one major problem: sandy barrier islands are rarely built around some earlier feature which was then partly drowned.

There are, at various places around the Gulf of Mexico, barrier islands the origin of which cannot be explained by any of the above hypotheses. These islands were initiated in some other way, although there is no doubt that, once they were created, many of them were augmented by material from offshore. It is the purpose of the present paper to note certain barrier island features which require a different mechanism.

Energy Constraints

A very narrow barrier island (less than about 500 ft wide) may be subjected to sufficient overwash and wind work that it migrates actively shoreward, narrowing the lagoon behind it. Barring a major change in sea level, such an island should in due time reach the mainland beach, where it will cease to exist as an island.

If the island is too wide to be migrating, it may undergo erosion on the seaward side, thus growing narrower with time. The initial rate of narrowing and the rate of migration, later, should depend on the coastal wave-energy level, provided the grain size is essentially uniform from one example to another.

Therefore we should expect such a history to unfold more rapidly along high energy coasts (such as the Atlantic and Pacific shores of the U.S.) than along low-to-moderate energy coasts (such as around the Gulf of Mexico). At a given date, it is more likely that island migration will have destroyed all parts of its original geometry, in a high energy setting, hence one is more likely to find clues to the original island position and character in a low energy setting. Papers such as the one by Dillon (listed above), illustrate this comment.

Many of the existing hypotheses come from high energy coasts, which are not the best places to look. We therefore turn to regions of lower wave energy. Good examples should be found around the Gulf of Mexico, where low sandy shores and moderate wave energy levels are common.

Island Nuclei

Many barrier islands on the coasts of the Gulf of Mexico contain one or more nuclei; island growth has taken place more-or-less seaward from these nuclei, which are the oldest parts of the islands. The nuclei were, at one time, separate islands; the oldest beach ridges typically "wrap around" them on two or three sides, showing that they were not remnants of spits or other earlier larger features. The islands grew bigger with time because of a local "equilibrium of abundance" of sand, rather than a regime of erosion.

The younger "growth" areas are commonly marked by sequences, or sets, of beach ridges; such features are not visible in the nuclei. The question of the origin of many barrier islands on sandy coasts must be closely related to the question of the origin of the nuclei. But the nuclei appear to have no distinguishing marks that in themselves might help explain their origin. They are small (compared with present typical island size), more-or-less oval, arranged in chains having spacings of a mile or more, and occur typically one or a few miles from the mainland shore. A dune origin is hard to visualize. Certainly modern coastal dunes in the area do not have appropriate geometry.

Felix Rizk, who has been studying coastal sediments in the Florida Panhandle for about seven years, has had a keen interest in island nuclei, and has sampled several of them in detail. Some of his data, kindly made available prior to his own publication, include granulometric and other work on sands from two such nuclei, with 10 or more samples from each one.

The mean size is 0.24 mm for the one, and 0.22 mm for the other. These are typical values for his study area, and reflect a general coarsening trend, in one direction, which he found in all of his other samples.

The means of the standard deviations are 0.382 and 0.378, respectively, which are typical of beaches in this part of the world, where values commonly fall in the range 0.28-0.50. These values are a bit larger, numerically, than the sands (0.35) in the beach ridges which are adjacent to, but younger than, the nuclei. In an evolutionary scheme, with only a single dominant transport agency (beach-and-nearshore wave action, in this case), the adjacent beach ridges should indeed have slightly better sorting. Hence it appears that the nuclei amd the subsequent ridges fit into a single historical sequence.

The skewness values for the two nuclei are -0.195 and -0.0392. These numbers are typical of beach or river sands, but are not close to representing dune or sub-aqueous settling. The suggestion of a drowned dune is not supported at all. The suggestion of a river deposit must be set aside, for several reasons, the numerically low standard deviation and the very small tail of fines being only two.

The kurtosis values are 4.129 and 4.564. These indicate moderate wave energy levels (Tanner 1990), much like what can be seen in the area today. Skewness is more negative in the nuclei, less negative in the younger beach ridges, and kurtosis is the same in both cases. The changes in standard deviation and kurtosis, quoted here from the work of Rizk, are specifically indicative of maturing of beach sands over a period of time.

Therefore the granulometry indicates that the nuclei were formed in the same way as the beach ridges, by swash action. In other words, even within the nuclei, the evidence is for wave work. Yet it must be remembered that these nuclei, prior to the addition of younger beach ridges on two or three sides, were small isolated sand bodies a few miles offshore from the mainland. And the sub-aerial parts were not dunes.

The landward sides of some of the nuclei have been cliffed by lagoon waves. The material exposed in this fashion has not, as yet, produced any evidence for dune growth.

A single modern barrier island may have zero to four (or more?) recognizable nuclei. Barriers that are very narrow (perhaps less than about 500 ft wide) do not show any nuclei, and apparently do not have room for any. However, if a given barrier is narrow because it is migrating landward, nuclei on this island should have been destroyed long ago.

These nuclei appear to date largely from about 1,000-2,000 B.P. Such nuclei have not been recognized at many places, or have not been preserved for easy inspection, on islands that date back to about 3,000-3,500 B.P. This may be because the appropriate parts of these older barrier islands are now drowned (but drowning did not initiate these islands; it took place after they were already in position).

Exceptions

Many barrier islands do not have recognizable nuclei. There are several reasons for this. (1) Some are very narrow (<500 ft.), and are migrating landward by a "roll-over" process; the earliest parts have been destroyed already (such as parts of St. George Island, Fla.; Schade, 1985). (2) Some are being eroded severely on the lagoon side, and the oldest parts have been lost. (3) Some were initiated more than 3,000 years ago, when sea level was five to 10 feet lower than at present, and subsequent rises have permitted either total drowning or burial by younger sand. (4) Some were created on the "annual tide" tidal flat (Tanner and Hummell, 1989) where the water level rises and falls five to 10 feet almost every year. There probably are other reasons also.

Each exception must be considered in the light of its age, location and prevailing conditions. After exceptions of these kinds have been removed from the list, the incidence of nuclei is still high.

Moving Shoal

Johnson Shoal (Lee County, on the lower west coast of the Florida peninsula) may provide some insight into the origin of nuclei. The shoal appeared for the first time on maps and charts, in 1863, in water 10-20 ft deep, and has been migrating landward (eastward) ever since. Seven maps and charts from various dates and many sets of black-and-white aerial photographs have been used to produce a history of shoal migration. By December 1988 welding of large parts of the shoal onto the shore of Cayo Costa island was already under way (Tanner 1989).

The migrating shoal contained more than 13 million cubic yards of sand (more than 10 million cubic meters, with a mass of 10 trillion Kg). Known nuclei on other islands are commonly about this size.

Part of the shoal surface has been awash in many of the aerial photographs, starting in 1944. The outline of the exposed part has been, in general, V-shaped, with the apex of the V pointing seaward.

The moving shoal did not develop from dredge spoil (there has been no dredging of this magnitude in the area), a spit, a drowned dune or a fault: the water in the area was meters deep before the shoal first appeared. The initiation must have been a natural non-tectonic event: Emergence of a shoal since 1863 without notable changes in sea level or wave climate. Perhaps such events were more common at some moment in Late Holocene time, and account for barrier island nuclei. This statement raises two interesting questions: (1) How could such a shoal be converted into an island nucleus? And (2) How come conditions were better suited, for such events, say 2,000 years ago, than they are today?

Hypothesis

A small sea level drop (about 5 feet) would be enough to convert such a shoal into a small island, which would then show no distinctive markings, until later growth added beach ridges and/or dunes. Small drops, like this, in middle-to-late Holocene time, are now known (Tanner et al 1989). Johnson Shoal is being welded against a pre-existing shoreline, and will not form a new island. This is because there has been no suitable sea level drop in the last 130 years.

The central idea here is that a shoal can emerge and become an island by means of modest water level changes. Such a change in water level may be small and perhaps short-lived, as during a storm, or may last for a longer period of time. In the Gulf of Mexico area, sea level dropped three feet or more at least twice in middle-to-late Holocene time: once at roughly 4,000 B.P., and a second time about 2,000 B.P. Many barrier islands may have been initiated at one or the other of these times, with obvious growth histories well under way a century, or a few centuries, later.

The oldest known barrier islands along the Gulf of Mexico coast of Florida were initiated about 3,500 B.P.; two examples are St. Vincent Island, southwest of Tallahassee (Stapor and Tanner, 1977), and Sanibel Island, south- west of Ft. Myers (Stapor et al 1988). Several other islands apparently date from about 2,000 B.P., or a bit later. A third category of islands is not represented by dated materials that define the time of initiation, but this fact cannot be used to infer a time of nucleus-building other than the two stated in this paragraph.

A fourth category includes a few examples which were initiated about 1,000 B.P.; two examples are Mesa del Gavilan and Brazos Island, east of Brownsville and south of Port Isabel, Texas (Tanner & Hummell 1989).

Otvos (1970) produced an "islands from shoals" hypothesis. He stated in his abstract that "Historical evidence and drilling results... indicate that barrier islands form by upward aggradation of submerged shoal areas." In his text (p. 243) he stated that "Several . . . examples . . . took place during historic times." But in the following sentence he explained that this occurred by island migration ("Barrier islands . . grew westward by building shoals up . . . while the opposite ends were reduced by erosion . . . " (p. 243).

In contrast, the hypothesis stated in the present paper is that isolated shoals — during a certain and specific sequence of events — can turn out to be above water level, hence become islands. This is visualized without any effects from any adjacent island, spit or mainland. The necessary event is a small sea level drop, perhaps in the waning stages of a major storm, but more likely over a longer period of time. The island forms in place. If there is an abundance of sand, it may grow larger with time. After it has grown larger, the original nucleus may be preserved, on the lagoon side, as a more-or-less featureless sand mass. Along low-to-moderate energy coasts it stands a reasonably good chance of being preserved for a while.

The present hypothesis may explain the origin of many coastal island nuclei, which formed offshore without any help from dredge spoil, drowned dunes, growing spits, faulting, warping, or other such popular explanations. Once such a nucleus has been formed, there will be no problem in enlarging it, if there is a local excess of sand ("equilibrium of abundance").

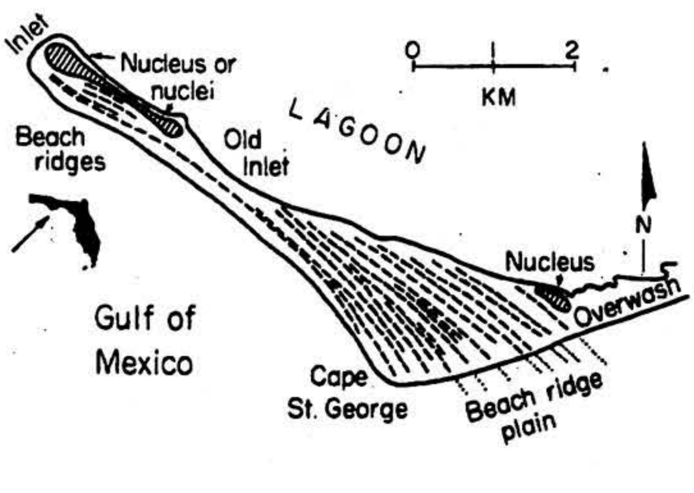

Figure 1. Little St. George Island, on the southern coast of the Panhandle of Florida, is really the westernmost part of St. George Island, but it appears to have had its origin as two (or three?) separate smaller islands, which have been welded to the main part of St. George Island later in its history. Of the two (three?) nuclei now visible on Little St. George, the eastern one has been augmented by later growth of a wide beach ridge plain, and the western one (or two?) has grown only slightly since initiation. The old inlet between them was plugged roughly 150 years ago, but the beach ridge pattern shows clearly the history of narrowing of that inlet.

The necessary ingredient is a very small sea level drop (perhaps three to five feet) to stabilize a shoal. This small drop would go undetected in any sea level history which is limited to a rising limb and a flat segment.

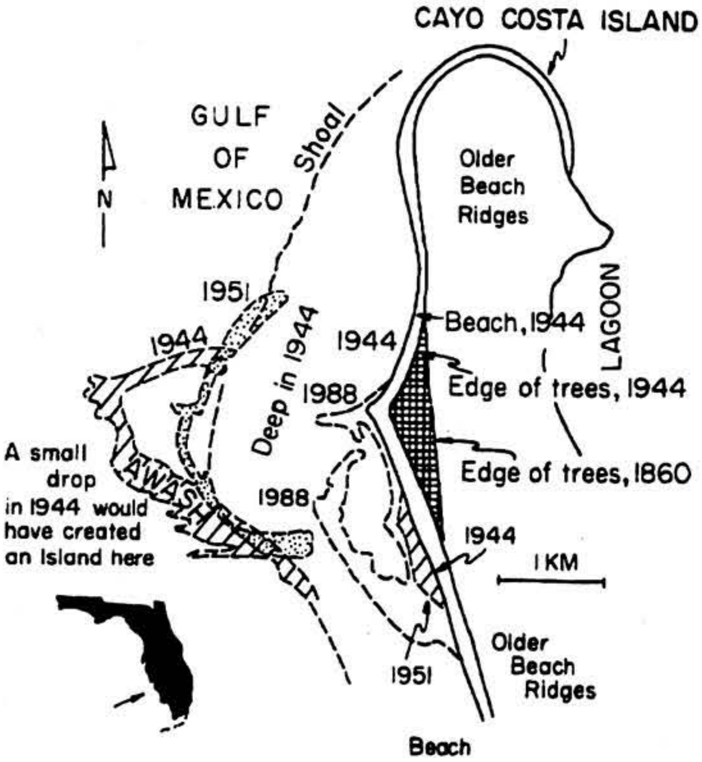

Figure 2. The northern end of Cayo Costa (island), on the lower west coast of the Florida peninsula, and Johnson Shoal to the west. The shoal was present, but not emergent, on the nautical chart of 1863. Positions of the emergent shoal, shown for 1944, 1951 and 1988, were taken from black-and-white vertical aerial photographs. In this case, without a suitable sea level drop, the shoal is being welded onto the older island. A sea level drop of three to five feet, between 1865 and 1940, would have converted the shoal into an island nucleus.

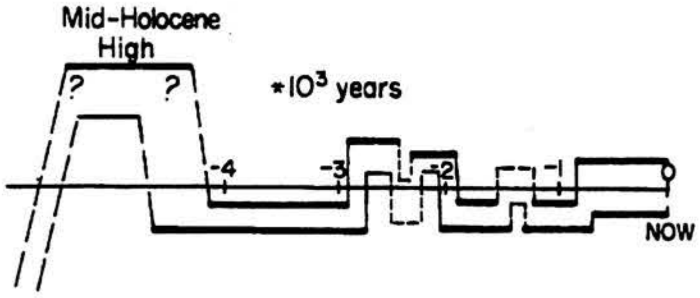

Figure 3. Sea level history for the Gulf of Mexico, modified from Tanner et al (1989) by including more of the changes shown in the print-out underlying their fig. 4-B than in their summary (their fig. 8). The dashed lines in the present figure indicate the added detail. According to this representation of the original data, the formation of island nuclei should have been concentrated around 1,800 B.P., possibly around 2,500 B.P. or 1,200 B.P.

CONCLUSIONS

The hypothesis stated here is that a small drop in sea level (e.g., three to five ft.) can convert a shallow but non-emergent shoal into a small island, which can be built up to a more stable geometry by swash action. Data now available show that sea level drops of about this magnitude have taken place several times during the late Holocene. It is also possible that such a drop could have taken place in the waning stages of a major storm, an event that might have been especially important if a given shoal had been built upward somewhat during the high-water stage of that storm.

A small island of sand, created by a small sea level drop, in an area of an abundance of sand, should then grow by addition of beach ridges (or other deposits) on one-to-three sides. The original island is here termed an island nucleus.

Sandy island nuclei have been found in many of those Gulf of Mexico coastal barrier islands which were initiated some 2,000 years ago, at (or not long after) a sea level drop of three to eight feet. In the study areas, very few barrier islands were formed at any other time, except prior to 3,000 B.P. during an interval for which we now have very few details.

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Appendix VII

Tanner, W. F., 1991, Suite statistics: The hydrodynamic evolution of the sediment pool: [In] Principles, Methods and Application of Particle Size Analysis, (J. P. M. Syvitski, ed.), Cambridge University Press, Cambridge, p. 225-236.

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16 Suite statistics: The hydrodynamic evolution of the sediment pool

WILLIAM F. TANNER

Introduction

For a century or so the purpose of making grain size measurements was to determine the diameter of a representative particle. This is useful when one is studying reduction in grain size along a river (e.g. Sternberg, 1875). But it is a simplistic approach, and one is entitled to ask: Is the mean diameter the only information that we wish to get? Or does the simplicity of this first step make us think that we have now described the sand pool?

When we measure grain size, what do we really want to know? This does not refer to whether we measure the long axis or the short axis of a nonspherical particle, or whether we approximate the diameter by measuring a surrogate (such as fall velocity). Rather, we ask this question in order to get a glimpse of how far research has come in understanding transport agencies or conditions of deposition, and of the degree to which we might reasonably expect to improve our methods of environmental discrimination.

Can a set of parameters that describe a size spectrum for one sample permit us to compare this sample with some other, perhaps from a different transport or depositional environment? A positive response implies that a single sample may be adequate to describe the parent sand body.

Do we want to know about variability within the sand body, thereby requiring a suite of samples? This might suggest that there is only one kind of variability (hence a single parameter will do), or it might mean that we will have to explore many kinds of variability.

Do we wish to see if there is more than one sand pool contributing to the sediment body? "Sand pool" needs an improved definition, but presently includes:

(a) material presently being added (but not necessarily deposited) at the site;

(b) material located "upstream" of the site and in transport toward it; and

(c) material already present.

This concept is more easily applied to river sands than to a wide, shallow, near-shore depositional area.

Do we wish to identify any characteristics of the transporting agency? Moving from "simple diameter of one sample" to "transport agency" is a big step, and it cannot be done by using simple theory. If we are going to undertake to answer questions such as these, we must make determinations beyond simply specifying a "representative diameter."

A good deal of work has been undertaken on trying to answer such questions, much of it at Florida State University. Many environments have so far been sampled, with thousands of samples. The basic environmental identities have been as follows: dune, mature beach, river, tidal flat, settling (or closed basin: lake, lagoon, estuary, interior seaway, etc.), offshore wave, and glaciofluvial. Not all have been treated equally; for instance, glaciofluvial materials and offshore wave sediments are poorly represented. Both modern and ancient environments have been studied and sampled in the field.

Most of the terms used here are familiar ones, such as mean and standard deviation (but as calculated numerically with the method of moments); two, however, require a note of caution (Hoel, 1954; Blatt, Middleton & Murray 1980). "Skewness" and "kurtosis" refer to some form of the third- and fourth-moment measures, respectively. The actual words have been taken, in part of the literature, to identify specific geometric features of a plot of the distribution; this is *not* the intent here. For present purposes, skewness and kurtosis are convenient labels for certain moment – *not* graphic – parameters. They do not require, but may correlate with, a specific curve shape. An additional point should be made regarding skewness. This term is used to mean (in general) an asymmetry of the distribution. Positive and negative skewness cannot be defined from a priori considerations. But Folk (1974, p. 52) and Blatt et al. (1980, p. 46) used "positive skewness" to identify a sample with many classes in the fine tail, and this usage has been followed here. Phi measure has been used throughout, unless indicated otherwise.

Control factors

Air versus water

The mass density of a single grain in air is quite different from that in water. The practical effect is that realistic local variations of air velocity, by a stated amount, are more important in moving a specified grain (such as quartz sand) than are the same variations in water velocity. A unidirectional flow of water typically transports a greater range of grain sizes (provided that they are available) than does a unidirectional flow of air. The standard deviation of the grain size tends to be numerically larger in unidirectional water transport than in unidirectional air movement. One cannot take a simple statement of the standard deviation of a single sample and translate that number to "transport agency" because some of the other influences mentioned here complicate the system too much. On the other hand, with suitable treatment, the standard deviation can be the basis for a powerful tool for discriminating among certain environments. One should note that in a few instances (e.g., on a beach), back-and-forth motions over a long period result in much better sorting than can be obtained in ordinary water or air currents.

New supply from upstream; through-flow; trapping; winnowing

A river carrying a large sand and/or coarse silt load may have an abundant new supply so that winnowing cannot be very effective. On the other hand, a more-or-less isolated sand shoal perched on a wide shallow shelf may have no new supply of sand, so winnowing can be very important.

Through-flow has to do with the ability of a transport system to carry certain sizes more or less continuously (time sense), such as the wash load concept dealing with fine silt sizes in an energetic stream: They are "washed" for long distances rather than resting on the bottom for lengthy time intervals on their way along the channel.

Trapping clearly can take place in ponds, lakes, and lagoons, but likewise is important in any kind of dead-end setting: a category that can be identified as the *closed basin* (perhaps even an interior or geosynclinal seaway). Settling may be the main hydrodynamic process. A simple example is the site where a high-energy, fine-sand-laden river flows into a coastal zone having very low wave-energy density. A large supply gives roughly the same results as a closed basin: probable dominance of the finer sizes, up to the limits of availability. Winnowing, on the other hand, tends to reduce the proportion of fines, as is well known.

Back-and-forth shuffling (BAFS) and net unidirectional sediment transport (NUST)

The basic concepts of back-and-forth shuffling (BAFS) and net unidirectional sediment transport (NUST) lead to an unexpected observation confirmed in both field and laboratory. Transport in an ordinary river is clearly characterized by NUST, and one can observe the result: Sand introduced upriver is carried downstream. Under a wave field, however, the primary effect is BAFS. There is commonly an asymmetry in transport effectiveness of water motion near the bottom, so the BAFS phenomenon leads to movement of grains of the same mineral (two different sizes) in opposite directions (see May, 1973). On a low-to-moderate-energy beach without a new supply, BAFS may be so efficient in and near the swash zone that the standard deviation of the grain size may be reduced to (or close to) what may be the minimum value for quartz: ~0.26. This is even lower than is found in most dune environments, where the mass density difference between air and sand (rather than BAFS) produces very good sorting.

Multistory (multitier/multilevel) turbulence structure

A single grain of quartz sand, settling in water, generates an eddy system with dimensions controlled largely by the size of the sand grain (Tanner, 1983). Eddies of a different scale may be formed adjacent to bedforms such as ripple marks and/or giant ripple marks. Sandbars and sandbanks are typically responsible for a third scale, and river bends create turbulence at a fourth level. It is not known how many stories may exist, but the number could reach six or more. In certain environments, the structure generally has only one or two levels. The turbulence structure is much more complicated (of higher numerical order) in a large, energetic river than on a low-energy beach. The standard deviation of the grain size distribution tends to be numerically smaller as the number of stories decreases (within the limits of availability). A high-order system (many stories) typically produces greater mixing of sizes at any one locality (if such sizes are available).

Grain–grain interactions

Because the eddy system generated by a single grain may occupy a volume orders of magnitude larger than the grain itself, interactions between grains may be frequent and important (Tanner, 1983). These include trapping, tailgating, and ejection, and involve the motion of one grain fairly close to another, perhaps of dissimilar size; the two may then be deposited together. The result is a significant numerical increase in the standard deviation compared with what would have been obtained had there been no such interactions.

Transport directionality

Unlike BAFS (under one wave train), this has to do with differences arising from varying wave approach angles and the mixing of two (or more) sand pools that may result. Such mixing tends to increase the standard deviation numerically, and generally modifies other parameters as well.

Bivariate plots

Sedimentologists have long tried to make environmental sense out of bivariate plots of parameters that describe a sample size spectrum. The investigator selects two parameters (such as mean size and standard deviation), and plots them against each other. There are many examples in the literature (see, e.g., Friedman & Sanders [1978, pp. 78–81], where skewness is plotted against sorting).

The results have been less than enchanting, for several reasons (Socci & Tanner, 1980):

1. *sampling technique* (taking too large a sample; cutting across many adjacent laminae);

2. *lab procedure* (using whole- or half-phi screens instead of quarter-phi sieves; making more than one split, thus escalating the splitting error; using too short a sieving time; putting too large or too small a sample on the coarsest screen; and so on);

3. *graphic or other low-precision parameters* (e.g., the sorting coefficient instead of the standard deviation);

4. *overlimited options* (e.g., beach versus river, as if dunes and other settings can be ignored).

In Friedman & Sanders (1978, p. 78), beach samples are compared with river samples by plotting "simple skewness measure" against "sorting measure" (their terms for graphic measures). The dividing line that was drawn between the two number fields is far from straight, does not emphasize anything like a natural division, and for some twenty-seven samples gives the wrong answer. Use of moment measures (p. 81) produces an improvement (perhaps nineteen misidentifications), but the dividing line is still complex, many samples of both types cluster on or near it, and the number field for beaches is centered within that for rivers. One understands why many workers have given up on the procedure. However, the basis for this kind of diagram is hydrodynamic (BAFS for beaches vs. NUST for rivers); it lacks only a small modification to become a valuable tool.

An obvious way to improve the graph is to define sample suites, by field or subsurface study, and plot only suite-mean values for each parameter. This greatly reduces the scatter, minimizes (perhaps eliminates) overlap, and pinpoints the center of gravity of the measurements for any one suite. Aberrant or anomalous values, still available to the investigator, no longer appear as clutter.

Ideally a suite contains perhaps fifty or more samples, but this is commonly impractical. Experience has shown that, for sand and coarse silt sizes, twenty samples generally make a stable suite, and in many instances twelve to fifteen may be enough; this can be verified statistically.

Advantages of the suite statistics approach include the following:

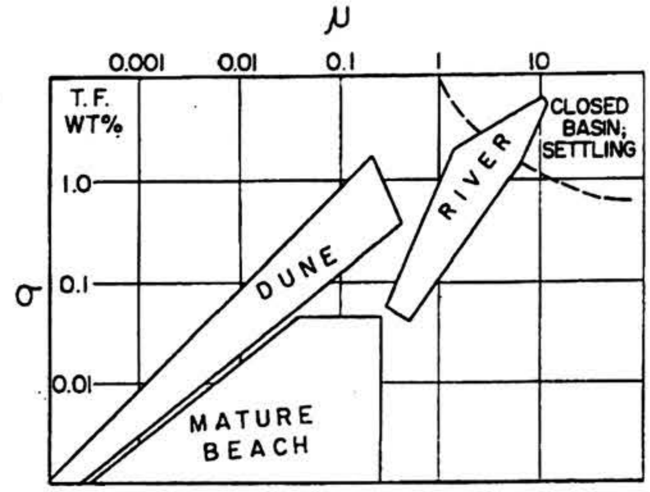

Figure 16.1. The tail-of-fines diagram. The means and standard deviations of the weight percents on the 4 ϕ screen and finer are shown here. Four fairly distinct number fields appear, as labeled above, with relatively little overlap. Many suites plot neatly in a single field. In certain other cases the apparent ambiguity may be useful; for example, a point at a mean of 0.01 and a standard deviation of 0.017 might indicate either dune or mature beach, and not formed in a closed basin. This diagram commonly gives a "river" position when in fact the river was the "last-previous" agency, but not the final one.

1. The number field* is smaller.
2. Anomalous points (although still present) do not clutter the plot.
3. Distinctions between transport agencies are more obvious.
4. Transition suites or mixtures may be easy to identify.
5. Three or more sedimentary environments may be represented conveniently on one graph.

Doeglas (1946) observed that the tails of the distribution provide much of the important information that is available to us; so we are less likely to be able to make fine distinctions by using the mean (surrogate for the first moment) than by using higher moments (such as the third and fourth). Therefore, we can construct one or more bivariate plots of tail data, using weight percents in the fine tail (material on the 4 ϕ screen and finer). For a suite of samples, one can plot the mean weight percent of the fine tail (4 ϕ and finer) against the standard deviation of the same fine-tail data (Fig. 16.1).

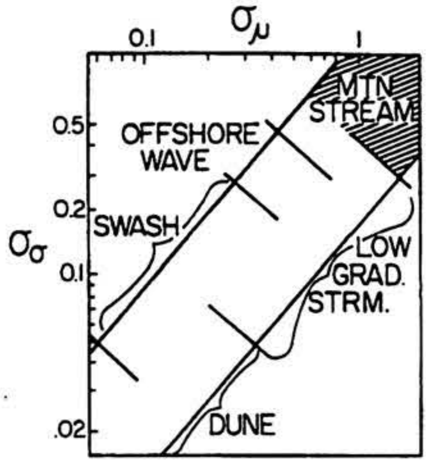

Figure 16.2. The variability diagram, showing the suite standard deviation of the sample means and of the sample standard deviations. Except for the extremes, the plotted position indicates two possible agencies (such as swash or dune). The decision between these two can be made, in most instances, by consulting other plots (such as Fig. 16.1). This diagram considers specifically the variability, within the suite, from one sample to the others.

This diagram has four reasonably distinct number fields: mature beach, dune, river, and closed basin (settling). The tail-of-fines plot works well because it depends on hydrodynamic factors: The suite mean tends to separate "large new supply" (river or closed basin) from winnowing (beach and dune), and the suite standard deviation tends to separate BAFS (mature beach and near-shore) and "large mass–density difference" (dune) from settling and poor winnowing. Furthermore, mature dunes (large mass–density difference) are generally readily distinguished from mature beaches (BAFS) because the number of transport events per year on the beach may be 10^5 or 10^6 larger than in a dune field.

A plot (not shown here) of standard deviation (S.D.) versus kurtosis K is commonly useful because a river, dune, or beach suite may appear within a small distinctive area, whereas tidal flat or other settling suites may plot in a long narrow band showing a very closely controlled relationship between the two parameters (form: $\ln K = a * \exp(-b * \text{S.D.})$, where a and b are numerical values to be determined for any given suite of samples; R^2 about 0.92–0.99). The standard deviation need not be small for this relationship to hold. On one well-studied tidal flat, settling effects produced a straight line of data points (Tanner & Demirpolat, 1988).

**Editor's note:* This is a numerical matrix of distribution parameters.

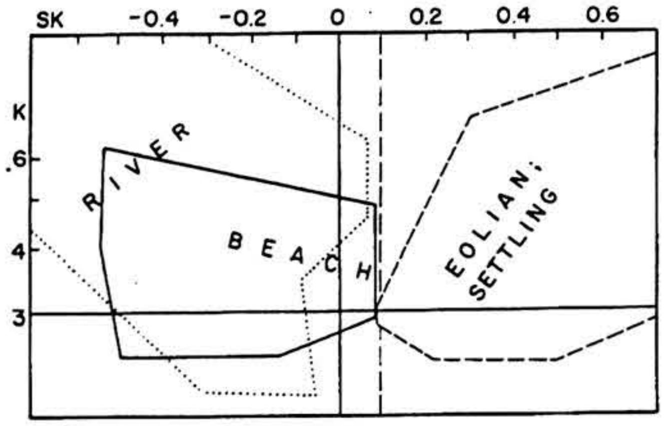

Figure 16.3. Skewness vs. kurtosis. The suite means of these two parameters are used. Positive skewness, as used here, identifies a geometrically distinctive fine tail; if there is also a distinctive coarse tail, it is the smaller (weight percent) of the two. The closed basin (settling) environment typically produces an obvious fine tail, much more so than beach or river sands. Eolian sands commonly have, instead of a well-developed fine tail, a feature called the *eolian hump* (cf. Fig. 16.5), which the skewness indicates in the same way as it does a distinctive fine tail. Therefore the two tend to plot together. Negative skewness identifies a distinctive coarse tail, either fluvial coarse tail (large *K*) or surf "break" (=kink in the probability plot; *K* in the range of 3–5 or so). Many river and beach suites appear in the same part of the diagram but are ordinarily easy to identify by using this figure first and then the tail-of-fines diagram (Fig. 16.1).

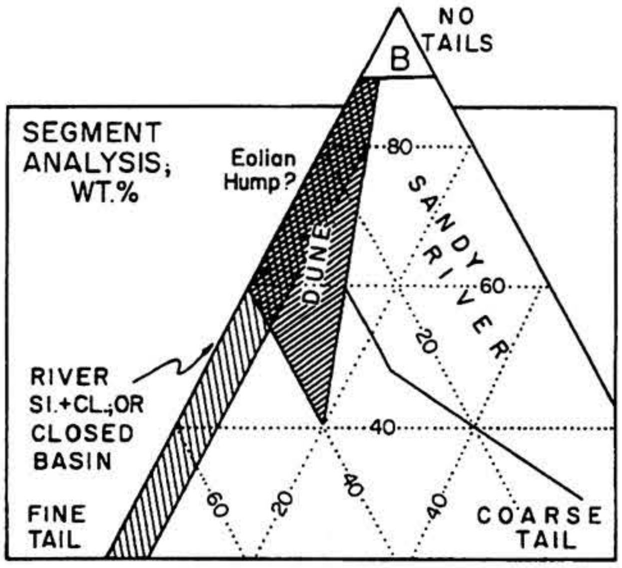

Figure 16.4. The segment analysis triangle. The procedure for picking segments and obtaining the necessary numbers is outlined in the text. The apex is characterized by very small or negligible distinctive tails ("no tails"), and the base (not shown) connects distinctive coarse tail (to the right) with distinctive fine tail (to the left). Four different environments are distinguished reasonably clearly, except for one area of overlap; in this area, one examines the probability plots for the eolian hump in order to see which of the two is indicated.

The variability diagram (S.D. of means vs. S.D. of standard deviations) typically places any given suite in one or perhaps two categories (e.g., dune or beach). Figure 16.2 identifies variability from sample to sample in a band ranging from "very small variations" (dune) to "very large variations" (high-energy stream), perhaps because it identifies the multistory turbulence level.

Skewness indicates the balance between the two tails. If the coarse tail is well developed and the fine tail small or nonexistent, a negative skewness (as defined here) results. If, on the other hand, the fine tail is dominant, skewness is positive. Experience to date is that beach sands (surf break on the probability plot) and river sands (coarse fluvial tail) tend to show skewness $Sk < 0.1$. Settling or closed basin deposits, with a well-developed fine tail but little or no coarse tail, typically show $Sk > 0.1$. Mature dune sands commonly have the *eolian hump* (a convex-up inflection, coarser than 50%, on the probability plot). Because the skewness parameter may see the main part of the sample as a large fine tail, it generally exceeds 0.1 for these sands. Therefore skewness can be combined to good advantage with some other parameter – perhaps kurtosis, as shown here, to make a useful diagram (Fig. 16.3).

The probability curve (see next section) can be divided into three convenient parts: A central segment (straight line) is identified first, and whatever is left over is then assigned to either the coarse tail or the fine tail. The percentages of these three parts can be averaged for the suite, and the resulting point can be plotted on a three-dimensional (triangular) "segment analysis" diagram, which separates mature sandy beaches (minimal tails) from rivers and dunes. Sand-and-gravel rivers are likewise separated from dunes and silt-and-clay rivers because the former tend to have larger coarse tails, and the latter, larger fine tails (like settling). Mature dunes can be identified provided the eolian hump is present on some of the probability plots (Fig. 16.4).

There are four well-studied moment measures (mean through kurtosis), several parameters derived from one or two tails, higher moments the meaning of which is not always clear, and other numerical values. Taken two or three at a time, these provide the bases for many bivariate plots, which are valuable tools for interpretation of agency and environment.

Contradictions?

In some cases many of the bivariate plots provide the same result – a single environment of deposition. These are the easy cases; but in many cases things are not that simple.

However, what might appear to be contradictory is commonly correct throughout, and helpful as well, because not all sand masses were moved by only one transport agency. Samples from the inner continental shelf (see Arthur et al., 1986) may give a river or fluvial identification, despite the marine location, because a sand mass delivered by one agency to another may not lose the granulometric fingerprint of the first until some considerable time has passed. Dune sand may be blown into a river or creek, and be reworked by running water. Suite analysis of the creek sands might then give a primary dune indication, yet also show that there have been complications. The analyst should not insist on selecting a single agency, but instead be aware that there may be two or more. Analysis of beach ridge sands commonly indicates both beach and dune origins, since sand beach ridges are typically built by both agencies (swash, wind). A mix of dune and beach indices might be formed in several ways, but unless there is other evidence for dune buildup, one should pick the beach as the preferred site.

Wind deposits filtered down from above, without any dune migration, have been identified correctly (see Tanner & Demirpolat, 1988) by suite methods as eolian plus settling, although beach and river components were suggested (also correctly) by the analysis.

There are many kinds of transitions and mixing, and the different suite parameters provide different kinds of clues to this – the hydrodynamic basis for any one parameter is not necessarily the same as for the others. Rarely, an environmental decision cannot be made.

Probability plot

The grain size distribution may be described by a package of parameters of various kinds (the early goal of achieving this with only one or perhaps two has not been realized). A graph may be used as a complement; for many size distributions, the complicated nature of the data makes a graphic display helpful. On such a graph one normally plots a transform of size (typically phi measure) versus weight, weight percent, or cumulated weight percent.

Histograms and cumulated S-curves fall into this category but suffer from a defect: They either display a slope reversal (which is confusing in highly detailed work) or exhibit marked curvature. In well-sorted sediments having few data points, these curves can be drawn in various ways without violating the points, and thus may be works of art rather than tools for study.

The purpose of a plot of a single sample is to provide information or an impression not readily gotten from the various numerical parameters. One therefore seeks a procedure that shows neither modal peaks nor artistic curve-fitting, and several are available. Well-known examples are the probability plot (Otto, 1938; Pettijohn, 1975), the Rosin-law plot ("crushed particle" distribution applicable to milled or ground-up material [Rosin & Rammler, 1934; Irani & Callis, 1963; Pettijohn, 1975]), and a method based on the log-exponential concept (Bagnold, 1941; Barndorff-Nielsen, 1977). Any additional variety can be created simply by noting that one must pick one or two transforms for the data (e.g., the probability plot uses a log transform for size [phi] and the Gaussian transform for cumulated weight percent). The Rosin-law plot has not been exploited much: Crushed materials follow it, but transported sediments do not. The Bagnold procedure has not been popular, perhaps because the computations required are time consuming, even on a computer.

There are certain advantages to using the probability plot:

Several varieties of suitable paper are already available commercially.

It is easy to make.

Modes and saddles are relatively easy to spot.

Certain parameters unavailable via ordinary statistical techniques can be read directly.

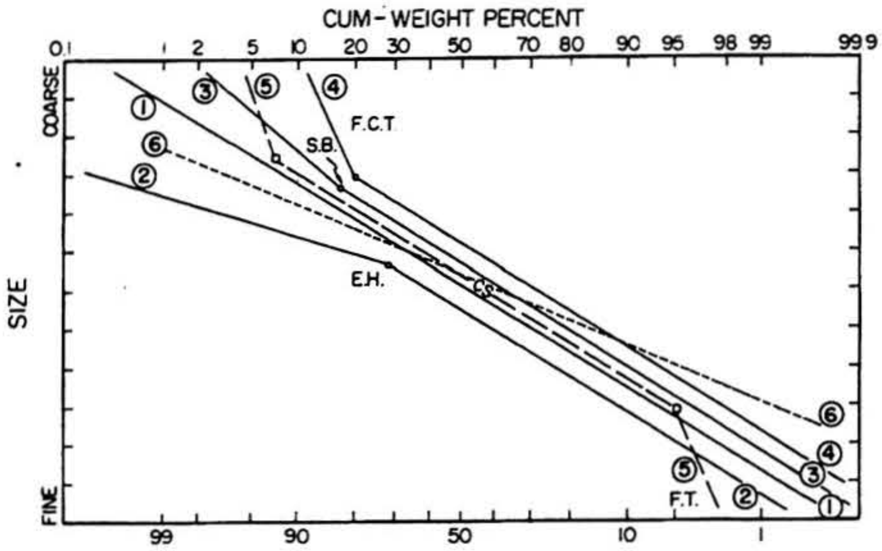

Figure 16.5. Diagrammatic probability plots. (1) The Gaussian, rare among sands. (2) The distinctive eolian hump (E.H.) is common, but not universal, in dune sands, and so far has not been observed in other sands that did not have any previous eolian history. (3) The surf break (S.B.) has been demonstrated to form in the surf zone, as the sorting improves. (4) The fluvial coarse tail is geometrically distinctive, but cannot be distinguished in every case from the surf break. (5) This curve has both a fluvial coarse tail and a fluvial fine tail; the central segment (C.S.) is the line between the two small squares. However, it is not the modal swarm (see text). (6) The modal swarm (a grain size concept, not a graphic one) obtained by subtraction from the original distribution; it shows the actual size distribution of the central segment (graphic device) of line 5. Lines of these kinds help one visualize the effects summarized in the bivariate plots.

Interpretation is fairly easy once the operator is used to its distinctive properties.

The main disadvantage (shared with some other methods) is that the learning period may be long.

The rationale for the probability plot may have been the idea that many (if not most) sands and coarse silts should be essentially Gaussian; therefore, one would quickly learn to distinguish "standard" sediments (straight line on probability paper) from anomalous ones. In fact, very few samples are perfectly Gaussian, but segments of the grain size distribution curve indeed are. Therefore, a better approach might be to study the probability plot in order to identify these particular segments, with an eye to providing an improved interpretation (as long as one remembers that they are segments of the plot, not components of the population) (Fig. 16.5).

Moss (1962–3) identified three common segments on such a plot and designated them by capital letters (A, B, C). Two of these are tails, and one is the central part of the curve. Rather than letters, the present writer prefers descriptive terms: *coarse tail* (segment), *central segment*, and *fine tail* (segment). The central segment commonly (but not in every case) crosses the 50% line, and generally shows numerically smaller (i.e., better) standard deviation (sorting) than the other two. Distinctive kinks, or inflections, mark their mutual boundaries. (The fine tail [segment] does not have the same definition or use as the tail of fines discussed earlier; here, it is set off by a kink in the curve, rather than by a stated size.)

The central segment must be distinguished from the *modal swarm*, which is a sample component (not segment) having a purely Gaussian form on probability paper. This component can be separated, in most instances, by simple subtraction. When combined with the pertinent tail components, the modal swarm yields the complete curve, which now shows segments (Tanner, 1983). Components, made of actual grains, are generally not visible on the plot. Segments are visible on the plot, but represent the effects of combining two or more components in one sample, and do not show quantities of various sizes actually present in any one component.

There is a widely used procedure based on the assumption that each straight-line segment on probability paper is also a component that has combined with its neighbors via butt-end joining (e.g., Visher, 1969). Because grain–

grain interactions in water provide results that, in turn, include significant misrepresentation of true grain diameters as part of creation of the perceived size spread, the butt-end-joining concept is erroneous. On the other hand, weighted addition of components, to create a segmented curve, is a better analytical concept than the simplistic and mistaken idea that segments are also the components. LeRoy (1981) stated one of several objections to the assumption that segments (rather than components) represent actual sand grain clusters in transport.

Bergmann (1982) examined significant settling effects on perceived grain diameter, and Tanner (1983) studied the hydrodynamic processes (capture, tailgating, ejection, and others). Their results show that butt-end joining is not possible, but that addition of overlapping components is not only possible but common. The resulting curve is, indeed, made up of two or more segments, but these segments are not the same as the actual components.

A few grain size curves are almost Gaussian on probability paper – mostly mature beach or dune sands, where long-term winnowing has been effective without the addition of new supplies. Other curves show the adjustment from one Gaussian form to another (Stapor & Tanner, 1975). Most curves have at least two segments and many have three, four, or more. (The number of segments does not specify the number of components; combining two well-sorted sands having considerable disparity in mean size may well produce a three-segment curve.)

The probability plot can be used:

to identify distinctive inflections (e.g., eolian hump, surf break),

to separate components where mixing is suspected,

to permit quick estimation of internal sorting,

to allow easy reading of certain useful parameters, and

to permit (where a linear suite is taken along the travel path) direct analysis, on the plot, of important hydrodynamic changes.

The linear suite

A suite of samples may be taken in any pattern preferred by the investigator: areally random, grid intersections, nested multilevel sampling, or others. One useful and time-honored procedure is to take the samples (in one suite) in a historically or hydrodynamically meaningful way. The latter is done when sampling a creek sequentially from headwaters to mouth. The former is done when a sandstone formation is sampled systematically from the oldest (base) to the youngest (top). A variant of the latter is to sample, along a suitable horizontal line, a geologically young and growing deposit, such as an aggrading beach.

The linear suite provides much more information than the same set of samples with relative positions in time or space unknown. A long stream without tributaries should yield a linear suite in which various size parameters (e.g., the mean) change in a predictable way from one end to the other. If tributaries are sampled, sediment mixing processes can be studied to good advantage in such a suite. If it is not known to be linear, this kind of work cannot be done.

Linear suites, unless the line is too short, commonly show changes. Down the river profile, tributaries may make important contributions. The changes in key parameters should correlate with the fact that not even the river profile itself is smoothly curving from one end to the other (Tanner, 1974). In time-dependent linear suites, historical events may be evident in the data.

The presence of changes or contributions, as stated in the previous paragraphs, may well preclude the use of simple regression models. One does not get high assurance by trying to force a nonlinear curve with several peaks into a simple linear model. If the nature of the change can be identified or assumed in some acceptable way, then detailed study can be undertaken on the separate segments of the line. Again, a good example is a linear suite along a stream profile: Peaks (or troughs) on the curve may correlate closely with tributaries. If so, the analyst should recognize this fact and adjust the treatment accordingly.

Demirpolat, Tanner, & Clark (1986) studied a line of samples across a beach ridge plain that has had a history of adding one new sand ridge every 20–25 years (roughly 180 ridges). In addition to areal sampling, they focused on a single transverse line, along which they sampled each available ridge (on that line). Because the ridges were clustered in visibly and measurably distinct sets, each containing some eight to twenty ridges, these workers were able to treat their samples in separate suites. One also can look at the whole sequence as a single linear suite and examine quasi-cyclical changes with time (oldest to youngest). Changes along the sample line are clear when plotted (sample by sample) in terms of standard deviation and/or kurtosis. Each of these two parameters showed striking changes having a quasi-regular periodicity of some centuries (two or more), and each change is associated with a change in ridge-set altitude. Because each set was deposited over an interval of centuries, these changes cannot reflect storms (or even stormy seasons); therefore these two parameters appear to identify small changes of sea level (of a meter or two, from plane-table profiling).

This work also produced other interesting results. On the tail-of-fines diagram (Fig. 16.1), successive sets of ridges plot as follows:

D, river (perhaps closed basin);
E1, mature river sediment;
E2, more mature river;
F, even more mature river;
G, beyond the river number field, to the edge of the "mature beach" number field.

Because this plot typically provides information about the "next to last" agency, the conclusion is drawn that set D reflects early reworking of river (probably deltaic) sands, and that by the time set G was being deposited, waves had come pretty close to producing mature beach or nearshore sand. This, of course, is correct, but could not have been deduced from the samples had they not been handled in linear fashion.

Storm data

Rizk (1985) studied beach sands along a large spit in the Florida Panhandle and determined grain size parameters along five transects taken at right angles to the beach, for both the high- and low-energy seasons of the year. His work provided a baseline data bank representing almost ten years since the area had last been struck by a hurricane (in 1975, by Eloise).

Shortly after he completed his analysis, three hurricanes (Elena, Juan, and Kate) affected the coast at intervals of only weeks (all in 1985). He therefore resampled his earlier transects at more or less regular time intervals: once shortly after Elena, once shortly after Juan, and twice within a month after Kate (Rizk & Demirpolat, 1986). Juan was the mildest of the three and did not produce any significant changes. This left six sample dates: two following a hurricane-free period of nearly a decade, two between Elena and Kate, and two after Kate.

The data for each traverse and date were examined in terms of the range for each moment measure; for example, for Traverse A, immediately after Kate, the range was calculated for the size mean, for the size standard deviation, and so on. The smaller the range, the less heterogeneity in that traverse on that date. The range of the mean size (in phi units) on Traverse A dropped from 1.0 prior to Elena to slightly less than 0.3 immediately after Kate, then climbed back to about 0.4 a month later. The standard deviation behaved in the same fashion (smaller values immediately after the storm). Changes were minor or not clear in the other parameters.

From their data the conclusion should be drawn that high storm energy resulted in mixing (homogenization), in contrast to the well-defined areal banding that existed after nearly a decade of relative calm and that was being reestablished a month or so after the third hurricane. For linear suites, this suggests that storm effects on this kind of coast are minimized in a matter of weeks to months, and therefore should not be expected to show up clearly in samples taken at much greater intervals than this. If major storms were common in the sample area (e.g., weekly intervals), then one would not expect the kind of recovery seen by Rizk & Demirpolat, and there would be no evidence for occasional violent storm activity.

Rizk & Demirpolat (1986) noted that whatever is represented (locally) by fair weather provides important long-term influences on the grain size distribution. The before- and after-storm data were also studied in terms of other suite parameters. The effect was greater suite uniformity after each storm. This is the same observation made from comparing traverses, but the presentation is different and the conclusions appear to be more general when seen in suite form.

Evolution of the sand pool

A suite may be taken in areal, linear, or some other fashion. An areal suite should approximate a fairly narrow time slice, spread over an area. If the area is large, local suites should be taken at various places (perhaps only a few meters to some hundreds of meters across). The suite analysis should provide roughly the same kind of information produced by isoplething each parameter, such as mean size, but with less variability and more different kinds of information. An *isopleth map* of mean size (or of coarsest median diameter, or of some similar measure) commonly pinpoints the part of the study area closest to the source. If this is all one wants to know, and if the simple isopleth map is clear, then suite methods are not indicated. On the other hand, suite procedures for a full house of parameters provide a great deal more information.

The linear suite may be geographical (e.g., along a river), as stated earlier, or it may have a time dimension. If the sample line goes, say, from oldest to youngest, then one has the opportunity of studying the evolution of the sand pool. One can plot various parameters – for individual samples or for small suites – along the time line, and observe the changes. If small suites (e.g., eight to twenty closely spaced samples each) are used, suite methods provide that there is very little noise, and one worries about neither the validity of statistical "lumping" techniques nor the exponential proliferation of numbers of samples in any useful nested-sampling design.

Beach ridge sets on a central traverse on St. Vincent Island have suite means and standard deviations of mean sizes (phi units) as follows:

	Set				
	D	E1	E2	F	G
Mean	2.2867	2.3812	2.4750	2.3045	2.1750
S.D.	0.0925	0.1014	0.0682	0.1324	0.0787

This produces a relatively smooth history of fining, followed by coarsening, from oldest (D) to youngest (G). The changes are real, as can be seen by inspecting the standard deviations: The mean for E2 is four standard deviations larger than the mean for G. The history of the offshore sand pool, for these ridges, includes an early fining sequence (the model of May [1973]), followed by coarser sediments after much of the fine-sand population had been depleted (not included, but implied, in the model). The time is ~2,000 years (Figs. 16.1, 16.6).

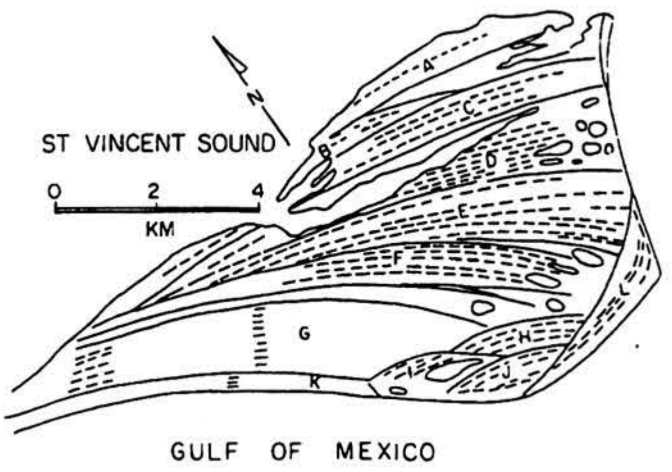

Figure 16.6. Sketch map of St. Vincent Island, Florida, showing twelve beach ridge sets easy to recognize on air photos or by plane tabling. Some of these sets, each consisting of ten to fifteen ridges and representing a few centuries, stand higher than others. Grain size parameters identify correctly those sets that stand high (or low).

Sets D–G are almost parallel with each other in map view (although set boundaries are distinct); however, they do not cover the full history of the island. Younger than G are sets H–L. Sets H, I, and J are located at the eastern end of the island, have distinctive map patterns including very short ridges, and do not parallel anything older; therefore, they do not belong in the same history as D–G. In fact, the suite-mean mean size for H–J is 2.3, an apparent fining after the previous coarsening. The offshore sand pool has been isolated for longer than the history of St. Vincent Island; hence it is unlikely that this is merely a "new wave" of fine materials, but from the same source as older ridges.

Alternatively we can see if sets H–J represent introduction of finer material from the east (St. George Island). The suite mean of H–J is clearly within the range of D–G, so it is not finer than the offshore sand pool may have been at an earlier date. It is finer than set G.

Other parameters may be helpful. The standard deviation of H–J is numerically larger (mean value 0.414, with a suite standard deviation of only 0.025) than any set in D–G (maximum, 0.39). The kurtosis of H–J is larger (3.936) than anything in D–F, and equally large with G. For low-to-moderate wave energy, these are distinctive results.

The map patterns show that these short, almost isolated ridges were supplied from the east; but the granulometry alone, with linear methods, indicates that a new source of sand became important in the study area between G and H. The history of this one island is really not the topic here. The key item is the chain of trends shown by sequential suites (or samples) in a linear system. Such a study yields more information than can be obtained by sampling in a nonlinear fashion.

Conclusions

The grain size distribution of a sand contains much information about transport, deposition, or both. Analysis of a single sample of that sand may not provide very much of the information since variability from one sample to another may be an important facet of the nature of the sand body. The joint study of ten or more samples from the same sand is much more useful.

Several effects or controls operate so that the suite of samples shows distinctive characteristics. Among these effects are the following:

1. the mass–density contrast between mineral in air and mineral in water;
2. supply rates, through-flow, trapping, and winnowing;
3. back-and-forth shuffling (BAFS) and net unidirectional sediment transport (NUST);
4. multistory turbulence structure;
5. grain–grain interactions; and
6. transport directionality.

New procedures have been developed based on the concept of the *sample suite:* a set of closely related samples taken from a single transport and/or depositional system. Suite data include the means and standard deviations of the usual statistical parameters, plus additional measures such as the mean and standard deviation of the weight percent in the tails-of-fines (4ϕ and finer). These can be plotted to good advantage on bivariate diagrams, where interpretation is reasonably clear. These diagrams are particularly useful because they show certain aspects of hydrodynamics, sediment supply and resupply, trapping (settling; closed basin), and similar items. The result is a markedly improved analysis.

Some of the advantages over traditional plots, which show all of the data points, are as follows:

1. The number of plotted points is now much smaller and easier to visualize.
2. Dubious or anomalous points, due perhaps to sampling problems, do not clutter the diagram.
3. The effects of various transport agencies are easier to differentiate.
4. Transitions (in a historical sense) from one agency to another are easier to identify.
5. Four or more environments are conveniently placed on any one plot, without confusion.

The use of five or six properly selected bivariate plots commonly provides additional information, such as "last previous agency," and may also give strong clues as to the reliability of the analysis. The use of linear suites, where appropriate, can pay off in terms of important geographic or historical information: for example, the maturing of a sediment pool, the change from one agency to another, changes in energy level or in sea level, or the advent of short-term contributions from outside the system.

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NOTES

Appendix VIII

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20 Application of suite statistics to stratigraphy and sea-level changes

WILLIAM F. TANNER

Introduction

The methodology underlying the work described in this chapter is given by Tanner in Chapter 16. Development of the basic procedures has at all times been coupled with field and laboratory work on modern sediments, in a variety of environments. Over the course of almost fifteen years, the data bank has grown greatly. The plots and other devices that have evolved have been based on that data bank. These methods are considered to represent an improvement over traditional procedures (interpreting one sample at a time). Because the suite of samples contains more useful information than can a single sample, the results obtained by using suite parameters should provide better, more detailed answers.

Certain standards have been observed: laminar sampling (where possible), precision sieving, ≤100 g of field sample, not more than one split, ≤50 g for sieving using 0.25ϕ screens, and 30-min shaking time (Socci & Tanner, 1980). All of the work has been focused on quartz-rich clastics in the coarse silt–fine gravel size range; sediments made of chemically mobile materials are not discussed here.

Modern environments

Many modern environments have been studied using suite statistics: inner continental shelves, beaches, beach ridges, coastal dunes, interior dunes, river channels, tidal flats, delta fronts, aeolian nondune deposits, and others. A few deposits are problematical, even though they accumulated in late Holocene time and have not been altered very much since deposition. Except for the latter group, all of the modern examples are of known (observed) origin; thus the results of using suite methods are necessarily correct in the simplest, most obvious cases (criteria were based on these cases). Only one easy example will be given, followed by a presentation of a few marginal and perhaps contradictory examples.

Cape San Blas

Cape San Blas is located on the Gulf of Mexico coast of Florida southwest of the city of Tallahassee and southwest of the village of Apalachicola. All samples were taken from the mid-tide position on the modern (medium-energy) sand beach. The suite means (and standard deviations) of sample means and standard deviations were 2.517ϕ (0.175ϕ) and 0.368ϕ (0.046ϕ). This is a well-sorted and homogeneous suite.

Suite statistics parameters are summarized in Table 20.1. If this were a set of samples from a lithified rock exposure, one should conclude without hesitation that the environment of deposition was open beach (not lake, lagoon, estuary, or any other small closed basin). One might also wish to infer that there was a river influence of some kind, perhaps earlier in the history of the sand pool; but it is clear from Table 20.1 that these sands do not represent a river deposit, and there is no specific unique evidence for a river source. The single dune item should not be given much weight either, even though wind work is common on beaches: The variability diagram merely does not distinguish (in many instances) between beach and dune.

Medano Creek

Medano Creek flows along the eastern edge of the modern sand dune field, in Great Sand Dunes National Monument, near Alamosa, Colorado, at an altitude of >2.3 km. Dune sand is blown by the wind along what is generally a west-to-east path. Therefore the creek has two main sources of sediment: the dunes to the west and the mountain range to the north and east. The creek bed was sampled at 100-m intervals, producing fifteen samples in what was presumed to be a single suite. The basic measures for the suite (suite mean and standard deviation) follow: diameter 2.195ϕ (0.218ϕ), standard deviation 0.396ϕ (0.053ϕ), skewness 0.1 (0.25), kurtosis 6.882 (3.952), and tail of fines (≤4ϕ) 0.001 (0.0005). The standard deviations of the

Table 20.1. *Summary of suite statistics parameters for Cape San Blas*

Mean of the skewness (two choices):	beach	river
Variability (of mean, of S.D.; two):	beach	dune
Relative dispersions (mean, S.D.):	beach	
Skewness and mean of tail of fines:	beach	
Skewness and S.D. of tail of fines:	beach	
Tail-of-fines diagram:	beach	
Comparison of tails:	beach	

means (0.218 ϕ) and standard deviations (0.053 ϕ) indicated that this is a uniform suite. Nevertheless the analysis was run with fifteen samples, then with thirteen, and finally only eleven samples. Discarding was done on the basis of anomalously high fifth and sixth moments. The mean and the standard deviation of the tail of fines (Fig. 20.1), coupled with the skewness, indicate that these are dune sands, if only two treatments are used ($n = 13$ or $n = 11$ samples).

Likewise, the large standard deviations of skewness and kurtosis indicate a dune origin. Two other plots show a settling process; but settling, as used here, covers several environments, including aeolian, small lake, lagoon, or other closed basin setting – hence this finding is not helpful. The variability diagram (Fig. 20.2) gives a choice of dune or mature beach. Probability plots show a faint but sharply developed coarse fluvial tail, not at all representative of mature sand beaches or dunes. There is a single aeolian hump on the probability plots; this (by itself) is modest evidence for dunes. The analysis indicates that these sands are probably aeolian (dune and/or settling), but might have formed on a beach. The probability plots provide the additional clue that there is a small (but not dominant) influence of stream type. The beach evidence vanishes when the suite is reduced to $n = 13$, and so is rejected.

A suite of twenty-one samples is available from the dunes proper. This suite is characterized by great homogeneity. Suite parameters clearly indicate dune or settling, and many probability plots show the aeolian hump. Two obvious differences can be seen on the probability plots: Aeolian humps are common in the dune sands, and a faint but sharply developed fluvial coarse tail appears in the creek samples.

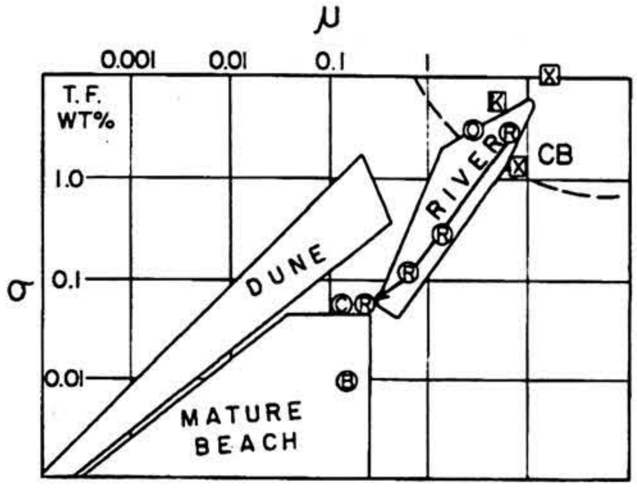

Figure 20.1. Tail-of-fines diagram: means versus standard deviations of sample values. The tail of fines is taken as the weight percent resting on the 4 ϕ screen, and finer. The closed basin (CB, settling), river, dune, and mature beach number fields are defined. ○, modern environments; □, ancient environments. Abbreviations: B, Cape San Blas beach; C, Medano creek; D, Great Sand Dunes; K, Oklahoma sandstones; O, Florida offshore; R, river; X, New Mexico sandstones.

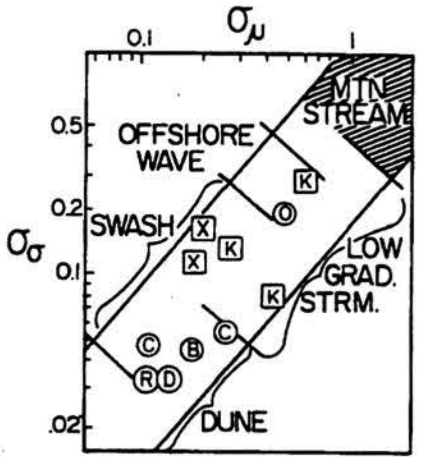

Figure 20.2. The variability diagram: standard deviations of sample means and of sample standard deviations. High energy is in the upper right, low energy in the lower left. Except for some dunes and high-energy streams, there are commonly two possibilities for any one point; this ambiguity can be resolved in Figure 20.1, Figure 20.3, or with some of the other methods given in text. See Figure 20.1 for key.

If the creek sands were lithified and exposed in an ordinary stratigraphic section, the environmental interpretation would probably be dune, but there would be a necessary note that there had been a minor fluvial influence of some kind. The analyst might consider the suggestion of a mature beach (hence the ocean coast), and might wish to opt for coastal dunes (a serious error), but a little attention to suite homogeneity would avoid this mistake.

Florida shelf

Arthur et al. (1986) studied surficial continental shelf sediments south of the panhandle (extreme northwestern part) of the state of Florida in the Gulf of Mexico. Their study area extended from a point south of Tallahassee, westward almost to the the westernmost boundary of the state. The east–west extent of the area is roughly 300 km, and the north–south width of that band is about 18 km, extending from 5.5 km offshore to almost 24 km offshore. Water depths were mostly in the range 3–30 m. There were 32 north–south sample lines, spaced about 9.5 km apart in the east–west direction, with 250 samples collected from the entire area.

The published report contains:

I. loran coordinates, water depth, and longitude and latitude for each sample;

II. the first four grain size moments, the tail of fines, and the median diameter for each sample;

III. running four-point averages, for each transect, showing smoothed mean, standard deviation, and weight-percent heavy minerals in each of three size classes;

IV. occurrence data for each of twelve heavy minerals in each sample; and

V. modal analyses for each of twelve minerals, in one size fraction (3–4 ϕ), for thirty-one selected samples.

In general, mean grain size coarsens to the west, but with large excursions, nearly as great as the entire range of values. The coarsest sizes were found opposite estuaries, and appear to reflect river channel positions when sea level was somewhat lower than it is now. The finest sizes, at the eastern end of the study strip, were found in an area where mean wave-energy density is extraordinarily low. Breaker heights are typically only 3 or 4 cm, despite the fact that this is an open sea coast (Tanner, 1960).

Standard deviations (running averages) of these size spectra decrease from about 0.94 at the eastern end to close to 0.67 at the western end, but with large excursions. Sediment was best sorted on a large shoal off of Cape St. George, where wave refraction and energy convergence are important.

A plot of skewness versus standard deviation from individual size spectra indicates samples in a beach or river regime, but fails to separate the two. The kurtosis versus skewness plot of Friedman & Sanders (1978) also did not make a clear distinction between these environments.

In this particular study, the large area clearly contains two or more sample suites, but the exact boundaries of the latter are not known. Therefore small subareas were treated, arbitrarily, as suites. Several results are apparent. The variability diagram of Arthur et al. (1986: cf. Fig. 20.2) placed the grand mean in the offshore wave or coastal plain stream category, but subareas also extended into the swash regime. The area is presently being reworked by offshore waves; it was subject to surf action in middle-to-late Holocene time; and the sands were indeed delivered to the region by one or more rivers.

The tail-of-fines scatter plot placed each subarea within the fluvial regime, and showed that these sediments are much more nearly like various rivers than they are like typical beach sands. The two environments, on the diagram, are separated by a factor of 10. This approach largely eliminates the uncertainty between river and wave (or beach). The location of the aeolian area on this scatter plot is well known, and these samples are in no sense aeolian.

Probability plots of representative samples show no aeolian hump, most having the obvious tail of fines (which eliminates the mature beach category) and a distinctive coarse tail (more typical of rivers than wave-dominated environments).

These samples were all obtained from the continental shelf, yet scatter plots of their suite statistics identify them as beach or river sands that still exhibit grain size characteristics of river sands. The apparent environmental interpretation is that these stream-deposited sediments date largely from a lower stand of sea level, and that there has not been enough time since they were laid down, and the water has been too deep, for the local waves to rework them to any great degree. Thus we should not expect that a sand mass, delivered from agency *A* to *B*, should instantly acquire the characteristics of the latter environment, which in due time could be imposed, especially as transport processes of the latter environment cannot operate effectively.

Further study of their data with several suite methods indicates the settling category for some of the subareas. One of several interpretations is that of open water, where storm waves can stir the bottom but fair-weather waves cannot – hence the stirred sediment settles back to the bottom, without evidence of wave action.

If this material were lithified and then examined in outcrops, one could immediately conclude from the lab work that these are river sands. Because channels (although present) are rare, one should also conclude that there was a second agency that spread the sediment in thin sheets over a large area without producing floodplain characteristics. If any of the many shells in the area were fossilized, and/or if numerous wave-type ripple marks were preserved, it would be obvious that a large water body was involved. If no such field evidence were found, and if exposures were adequate, it could be seen that various parts of the area gave different results: None favored an aeolian or beach origin, but fluvial, offshore wave, and settling were indicated. Perhaps these could be combined correctly. Lagoon, lake, or delta, fed by a small stream, do not seem to be reasonable choices.

Beach Ridge Plain

St. Vincent Island, Florida, has been studied extensively by many people because it is made up of some 180 well-defined sand beach ridges in a relatively simple pattern, showing a clear succession from the oldest (about 4,000 yr BP) to the present. The area is located southwest of the coastal town of Apalachicola, Florida, and is one of a chain of barrier islands and spits that rims the delta of the Apalachicola River (Chattahoochee River plus Flint River).

Demirpolat et al. (1986) summarize much of the earlier work and also add more granulometric information. The ridges occur in sets, clearly visible as such from the air or on the ground because of differences in soil gray scale, ridge height, soil moisture, and small changes in map orientation at set boundaries. There are perhaps twelve sets, with roughly fifteen ridges per set.

A centrally sited orthogonal traverse, about 4 km long, was sampled by two different investigators, on two different occasions, using standardized field techniques. Each worker did his own lab processing. For comparison, the two projects yielded suite mean sizes of 2.34ϕ and 2.32ϕ, and suite mean standard deviations of 0.385ϕ and 0.39ϕ. Sample mean diameters were within 10% of the suite mean. Sample standard deviation differed from the suite value by less than 14%. Therefore the grain size data represent a homogeneous suite from a central strip across the island.

For present purposes, fifty-nine ridges in the central strip were sampled, each ridge on the seaward face at half the mean altitude. Because of the great uniformity of the sand, these fifty-nine samples were taken to constitute one suite, but with the knowledge that several ridge sets were included. The numerically low suite value for the standard deviation indicates dune or mature beach, but not settling, river, glacial meltwater, or tidal flat. The suite skewness (–0.123) points to river or mature beach, but the first of these is no longer an attractive possibility. The variability diagram (suite standard deviations of sample means and of sample standard deviations; Fig. 20.2) suggests dune or mature beach, but the skewness value (Fig. 20.3) largely precludes the former. Taken together, the evidence identifies mature beach as the environment of deposition.

The tail-of-fines procedure (mean and standard deviation of weight percents on the 4ϕ screen and finer; Fig. 20.1) commonly gives last previous (penultimate) agency (as in the preceding section on continental shelf suites). For St. Vincent Island beach ridges, set D plotted with river or settling; at the time of set D, the ridges were being built more or less directly from river-mouth sediments. Sets E-1, E-2, and F plotted with rivers, but the three sets lie in a succession, each farther from the settling area than its predecessors; and set G appeared on the edge of the mature beach number field on this plot. That is, with time (from D through G), the sand became less and less like delta deposits and more and more like open beach sands. These

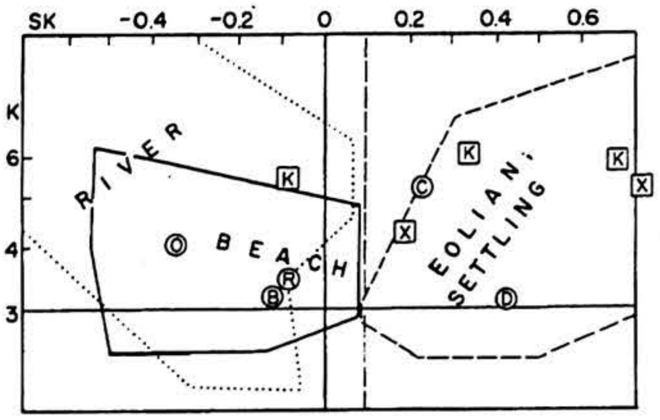

Figure 20.3. Suite skewness versus suite kurtosis. The primary dividing line is at a skewness value of 0.1, separating aeolian or settling sediments (to the right) from river or beach sediments (to the left). The skewness provides a comparison of the two tails, and the kurtosis indicates their size. In some instances, river and beach sediments can be distinguished on the basis of kurtosis. The latter (*K*) also provides a general clue to energy levels: small *K* suggests high energy, and large *K*, low energy. On the right-hand side, dune sands typically have *K* ≥ 3, and closed basin sediments may have *K* <3. See Figure 20.1 for key.

four sets span about 2,000 yr of more or less simple evolution of the sand pool.

At the southeastern tip of the island are several small ridge sets that do not belong with the main body of the island. These short ridges also indicated (with various criteria) settling, river, and mature beach, but also an aeolian influence. The combination of swash and aeolian effects is essentially standard in sand beach ridges (not necessarily in single massive coastal ridges [Tanner, 1987]). However, the primary agency was wave action (swash) with secondary wind work. This is true of most sand beach ridges that I have studied, where obvious wind deposition typically represents 5%–20% of the entire coastal ridge.

Table 20.2. *Mean/kurtosis of ridges*

Topographically low ridges	Ridges with low mean/kurtosis
1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6
15, 16, 17, 18, 19, 20	14, 15, 16, 17, 18, 19
46, 47, 48, 49, 50, 51	48, 49, 50, 51

The ridges crossed by the central transect were deposited in an unambiguous sequence from oldest to youngest. This fact provides much more information than can be obtained from a suite of random samples. Several parameters are of interest here, because set boundaries are clearly visible (e.g., on air photos), and therefore ridge sets can be studied as such. Certain ridge sets stand low relative to others. Each ridge set spans a few centuries, and therefore each has a vertical position that does not reflect storms or even stormy decades.

Where the mean/kurtosis parameter is numerically low, the ridge set was found to stand low. This is demonstrated in Table 20.2, where ridge numbers are from oldest to youngest. A critical mean/kurtosis value of 0.68 was used here; data were examined in terms of a three-point moving average (Fig. 20.4). Other statistical parameters successful in distinguishing between topographically high and low sets, using three-point moving averages, were 1/kurtosis (0.3), S.D./kurtosis (0.115ϕ), the differences of the standard deviations (which show changes only, but not positions), and differences of kurtosis (which also show changes only). Each of these five plots identifies either changes and positions, or changes, correctly.

Set means of the means and set means of the standard deviations provide some additional information. The sand got finer and better sorted from ridge 1 to 15 (a boundary value, as seen above); then coarser and less well sorted from 15 to 32 (another boundary value); and finally finer and better sorted from 32 to 45. There were matching changes in skewness and kurtosis, also. Ridges 15 and 32 appear to mark important boundaries in terms of these size parameters.

Each of these sets covers hundreds of years (e.g., ridges 15–20, plus any ridges missing on the traverse, times roughly 20 yr each). Therefore the numerical results show sand-pool effects, regardless of whether a low set represents a slightly lower mean sea level. Seasonal or storm events are too brief to be shown, but there is evidence for slower (few-century) modifications of the sand-pool history. Wave-climate changes are also not shown since differences in set heights are too large to be due to long-term wave changes. It is concluded that suite size

```
This is LINEAR.  Data source:STVIN.4AE.  N is  37 .  Mn/Ku Cut-off: .68
Std.D/Ku Cut-off:  .125 .   Mn/Ku MovAvgs Window= 3  and mean:  .7131271 .

  I     Std.D./K      Mean      Kurt.   Mn/Kurt. Mov.Avg. (incl. $)            I
Mean value of Mn/Kurt.:                                         #

    1    .096        2.318    3.928                             |               1
    2    .106        2.362    3.578      .619   LOW?    $       |               2
    3    .103        2.274    3.728      .667   LOW?        $   |               3
    4    .12         2.346    3.158      .662   LOW?        $   |               4
    5    .135    @   2.23     3.459      .677   LOW?         $  |               5
    6    .101        2.381    3.658      .665   LOW?        $   |               6
    7    .119        2.392    3.403      .692                 $ |               7
    8    .113        2.445    3.355      .729                   |  $            8
    9    .13     @   2.473    3.266      .765                   |     $         9
   10    .15     @   2.338    2.861      .792                   |       $      10
   11    .143    @   2.434    3.019      .793                   |       $      11
   12    .136    @   2.315    3.048      .74                    |   $          12
   13    .109        2.303    3.455      .703                  $|              13
   14    .123        2.297    3.33       .649   LOW?      $     |              14
   15    .096        2.355    3.924      .643   LOW?      $     |              15
   16    .12         2.293    3.542      .63    LOW?     $      |              16
   17    .122        2.212    3.406      .615   LOW?   $        |              17
   18    .11         2.14     3.844      .613   LOW?   $        |              18
   19    .088        2.435    3.819      .651   LOW?       $    |              19
   20    .138    @   2.306    2.897      .704                  $|              20
   21    .106        2.416    3.449      .741                   |  $           21
   22    .156    @   2.203    2.992      .796                   |       $      22
   23    .146    @   2.415    2.39       .813                   |         $    23
   24    .112        2.365    3.198      .772                   |     $        24
   25    .106        2.427    3.742      .71                    $              25
   26    .112        2.454    3.255      .731                   | $            26
   27    .116        2.518    3.121      .785                   |      $       27
   28    .151    @   2.238    2.8        .817                   |          $   28
   29    .126    @   2.468    2.918      .817                   |          $   29
   30    .117        2.531    3.136      .834                   |           $  30
   31    .135    @   2.474    2.901      .817                   |          $   31
   32    .132    @   2.35     2.962      .807                   |         $    32
   33    .116        2.457    3.153      .78                    |     $        33
   34    .11         2.566    3.327      .766                   |    $         34
   35    .151    @   2.188    2.931      .7                    $|              35
   36    .096        2.228    3.714      .649   LOW?      $     |              36
   37    .107        2.19     3.523                             |              37

Mean value of Mn/Kurt.:                                         #
  I     Std.D./K      Mean      Kurt.   Mn/Kurt. Mov.Avg. (incl. $)            I

This is LINEAR.  Data source:STVIN.4AE.  N is  37 .  Mn/Ku Cut-off: .68
Std.D/Ku Cut-off:  .125 .  The latter helps identify boundaries.
```

Figure 20.4. The ratio of mean to kurtosis, for each sample, along a time line across part of the St. Vincent Island beach ridge plain. The full output covers ridges 1 (oldest) through 59, but is not shown here for space reasons. The note LOW?, derived from the ratio itself, identifies topographically low ridge sets (not low individual ridges; these are three-point moving averages). In this area as on other sand ridges that have been studied, this ratio, or any of several other parameters listed in the text, identifies set vertical position changes and hence presumably small sea-level changes.

data provide useful clues to long-term wave-energy-level changes and therefore to small (1–2 m) changes in mean sea level. That this is not a geographically localized effect is shown by the fact that the same relationship between suite data and ridge height appears in data from Mesa del Gavilan, a beach ridge plain located southeast of Port Isabel, Texas (Tanner & Demirpolat, 1988).

What if this sand sheet were lithified, and then exposed at some future date? Almost completely without marine fossils, it might contain a few thin peat layers. Ripple marks are nonexistent; cross-bedding, if visible, would be largely in the 8°–20° range, dipping southward (at present, toward the open sea), but having a uniformity that might very well be puzzling. Perhaps the best information would be granulometric. One should be able to identify the sand as having been placed on the beach rather than in some other environment. River influence should be obvious, and one should even be able to point toward the river mouth (north of the oldest sands, by present coordinates).

Identifying modest sea-level changes conceivably would be possible, but the investigator would not be able to select sample sites on the basis of ridge geometry (as was actually done), and perhaps would not even be able to establish a linear suite.

Ancient environments

Oklahoma

The Vamoosa formation, of late Pennsylvanian age, was chosen for sampling. This sandstone and conglomerate unit is well exposed along several roads in Seminole County, in east central Oklahoma. It was selected because previous work (e.g., Tanner, 1953) showed that it contains (from north to south) sediments that represent seafloor, barrier island, and lagoon (or estuarine) environments of deposition. As part of a larger project, five sample suites, totaling forty-eight samples, were collected (Tanner, 1988).

The suites were taken along two lines that cross the axis of the barrier island at about 60°. One of these lines, representing the basal, or oldest, part of the formation, was 23 km long and included three suites: A on the northern (seaward) flank, B near the middle, and E on the southern flank of the barrier. There were ten samples in suite A, fifteen in B, and five in E. The other two suites (fourteen and four samples) were collected near the middle of the formation, on the northern flank of the barrier island. There were twenty-nine more samples from rock units higher in the section (slightly younger).

The three suites from the basal Vamoosa formation contained tail of fines with weight percents and standard deviations of those percents in the closed basin or settling category: quantities of sediment on the 4ϕ sieve (and finer) greater than found in most rivers. The tail-of-fines plot (Fig. 20.1) commonly shows the penultimate transport agency; therefore, these data may indicate a fluvial source.

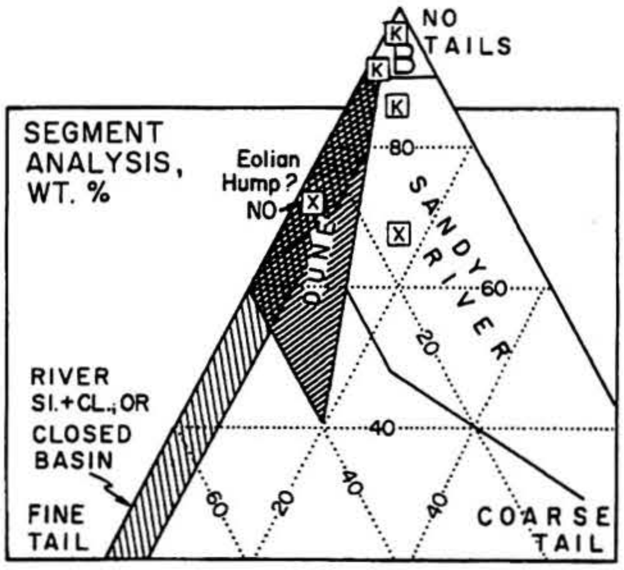

Figure 20.5. The segment analysis triangle. The raw data were taken from the probability curves for individual samples. Each curve was dissected into a straight-line central segment and two tails (whether straight lines or not). This provided three segments for each sample. Percentages were read for each segment, and the three mean values then calculated and plotted. The "B" near the apex marks mature beaches; other environments are labeled clearly. The main overlap involves dune (aeolian) sediments and clay- or silt-carrying streams; this ambiguity can be resolved, in most instances, by checking for the aeolian hump on the probability plots, and/or by comparing the mean sizes and standard deviations. See Figure 20.1 for key.

The suite mean values of skewness for the three suites plot as follows (Fig. 20.3): B and A (closest to the sea), settling or aeolian; E (closest to the fluvial source to the south), river. There was no clear evidence for an aeolian origin, so this option was discounted. The standard deviations of suite means and suite standard deviations indicate beach, offshore wave, or low-gradient stream (Fig. 20.2). The lack of coarse tails in these sand units – coupled with high weight percents in the central segment on probability plots (typically ≥90) – places A and B (seaward suites) with beaches, and E (landward suite) with rivers (Fig. 20.5). The relative dispersions of means and standard deviations (Fig. 20.6) indicate a beach origin for B, a probable beach origin for A, and a probable river source for E.

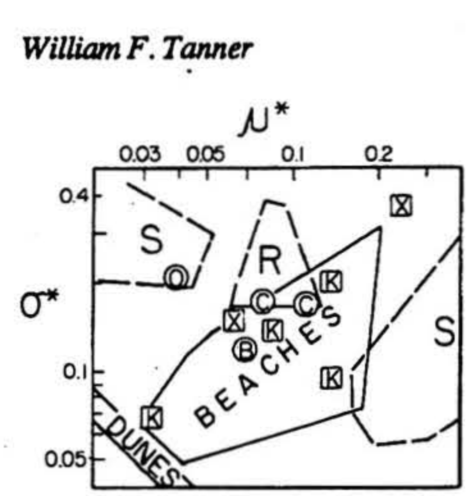

Figure 20.6. Relative dispersions of means and standard deviations, showing settling (S), river (R), beach, and dune areas. There is a small overlap at two places. See Figure 20.1 for key.

Suite E, taken within the lagoon (or estuary), appeared on bivariate plots with river environments. Suites A and B, on the other hand, showed clear beach characteristics, but also evidence of settling. This last indication is here taken to match the restricted (interior) seaway in which these sediments accumulated. The penultimate agency for all of the suites was indicated as fluvial.

Because the suite analysis provided the same interpretation as had been made on the basis of other information, the conclusion is drawn that the methodology was useful (Tanner, 1988). The suite approach did not produce as much detail as did the combination of fieldwork and paleontology, but in the absence of the latter would have reached essentially the same general conclusions.

New Mexico

The Yeso formation of Permian age is well exposed in many places in San Miguel County, in north central New Mexico. It is typically a thin-bedded sandstone, with lesser amounts of coarse siltstone and shale, and a few thin limestone beds. It lies immediately above the Sangre de Cristo formation, mostly of continental origin in this part of the state, and directly below the Glorieta sandstone, which contains wave-type ripple marks indicating fetch in the hundreds of kilometers. The Yeso itself also contains wave-type ripple marks, but all are small, ranging down to <1 cm in spacing. Based on this information, the Yeso was identified earlier as of tidal flat origin (Tanner, 1963).

Two suites (eight and twelve samples) have been processed from the Yeso; they are designated A and B. The two were collected within about a kilometer of each other, horizontally, but the former represents the middle of the formation, and the latter, the upper third.

Tail-of-fines data (Fig. 20.1) place both suites in the closed basin or settling category. This is taken to indicate the geosynclinal seaway in which Yeso sediments accumulated. The suite mean skewness value (Fig. 20.3) also indicates settling for each suite, although the two do not have similar values. The alternative is aeolian, but the fairly uniform thin bedding, the very small wave-type ripple marks, and the absence of any positive evidence eliminate this possibility.

Each of the two suites provides one clue suggesting a tidal flat depositional environment: the ratio of suite mean standard deviation to suite mean kurtosis (0.19 in each case). The relative dispersion of the means and of the standard deviations (Fig. 20.6) puts each suite in the beach category, and the variability plot (Fig. 20.2) shows each as beach or low-gradient stream. The latter, along with the wind possibility, must be rejected for lack of support; but most of the criteria indicate settling, which is consistent with the low-energy tidal flat environment. The interpretation to be drawn from the suite statistics analysis is closed basin or settling, probably beach or tidal flat, but with a possible river episode in its history. The ripple mark data indicate very small fetch values, in general only hundreds of meters or a few kilometers at the most. The Permian sea in Yeso time was actually much larger than a few kilometers, so the ripple mark measurements are taken to mean restricted ponds on the tidal flat, such as are actually observed on low-relief, low-energy, modern examples (Tanner & Demirpolat, 1988).

Conclusions

The suite statistics procedure requires that a suitable set of samples, from a given sand body, be used for analysis, and that suite parameters (such as the mean of the sample means) be employed for environmental interpretation. The results of such a study typically include one or more of the following: identification of a domi-

Table 20.3. *Summary of suite statistics results for examples in the text*

	CSB	Med	GSD	Off	StV	Okla	NewM
Skewness > 0. 1							
(2 possibilities)		D,S	D,S			D,S	D,S
Variability			D			S	S
Tail of fines						S	S
Aeolian hump			D				
Skewness < 0. 1							
(2 possibilities)	B,R			B,R	B,R	B,R	
Variability	B	B,D		B,R	B	R	
Tail of fines	B	?		S	R		
Fluvial coarse tail		R					
Segment analysis						B,R	B,R
Relative dispersion	B	B,R		S		B,R	?
Summary	B	?	D	B,R,S	B,R	B,R,S	B,R,S

Note: Only the first column shows a simple case: obvious uncomplicated modern beach. The other columns illustrate problems, commonly due to mixing of environments, or sequence of environments (such as dune-to-creek, or river-to-sea). A more detailed analysis is given in the text.

Abbreviations: CSB, modern beach; Med, modern creek in Great Sand Dunes; GSD, modern dunes; Off, Florida offshore, modern shelf; StV, modern beach ridge plain; Okla, ancient barrier island, lagoon, and estuary; NewM, ancient near-shore tidal flat; B, beach; D, dune or aeolian; R, river or creek; S, settling (closed basin, lagoon, estuary, lake, interior seaway, delta).

nant agency or environment (if there was only one), identification of a penultimate agency, evidence for combination of two agencies, details on maturing of the sand pool, and evidence for small changes in mean sea level.

Only one easy modern example has been included in this study. The other modern examples were selected to illustrate the kinds of problems commonly encountered. Although interpretation is not invariably easy, the results (Table 20.3 gives a summary) are nevertheless superior to what one gets by making single-sample statistical studies.

The ancient examples are representative of various projects that have been undertaken in that kind of work: Where other evidence has been available, suite methods have given essentially the same results. This provides some encouragement that, when other information is scarce or ambiguous, suite methods provide useful results.

However, some of the lithified sandstones (of unknown or uncertain origin) studied have not provided satisfactory answers: some because of pervasive silica cement, precluding lab analysis, and others because suite procedures yielded indicators of too many different environments. This is not a statement that the suite parameters were erroneous, but only that no clear interpretation appeared in the course of the work. Many modern sands represent mixed agencies, or transition from one agency to another (e.g., river to marine). The suite methods have been useful, in general, in these cases; the examples given are representative of the more difficult suites.

Despite problems that one encounters in using suite statistics methods, the results are much better than are generally obtainable by trying to base an analysis on data from individual samples. The method is not foolproof for various reasons, including inadequate number of samples, inadequate areal coverage, poor sampling technique, absence of a single well-defined environment of deposition, and (for ancient rocks) pervasive silica cementation. Perhaps the most important difficulty lies in the fact that certain sand bodies have been studied at a moment of transition; that is, when there is in fact no single responsible agency or environment. This may be problematic for our wish to erect sharply defined class boundaries, but it is not a problem in the method of study.

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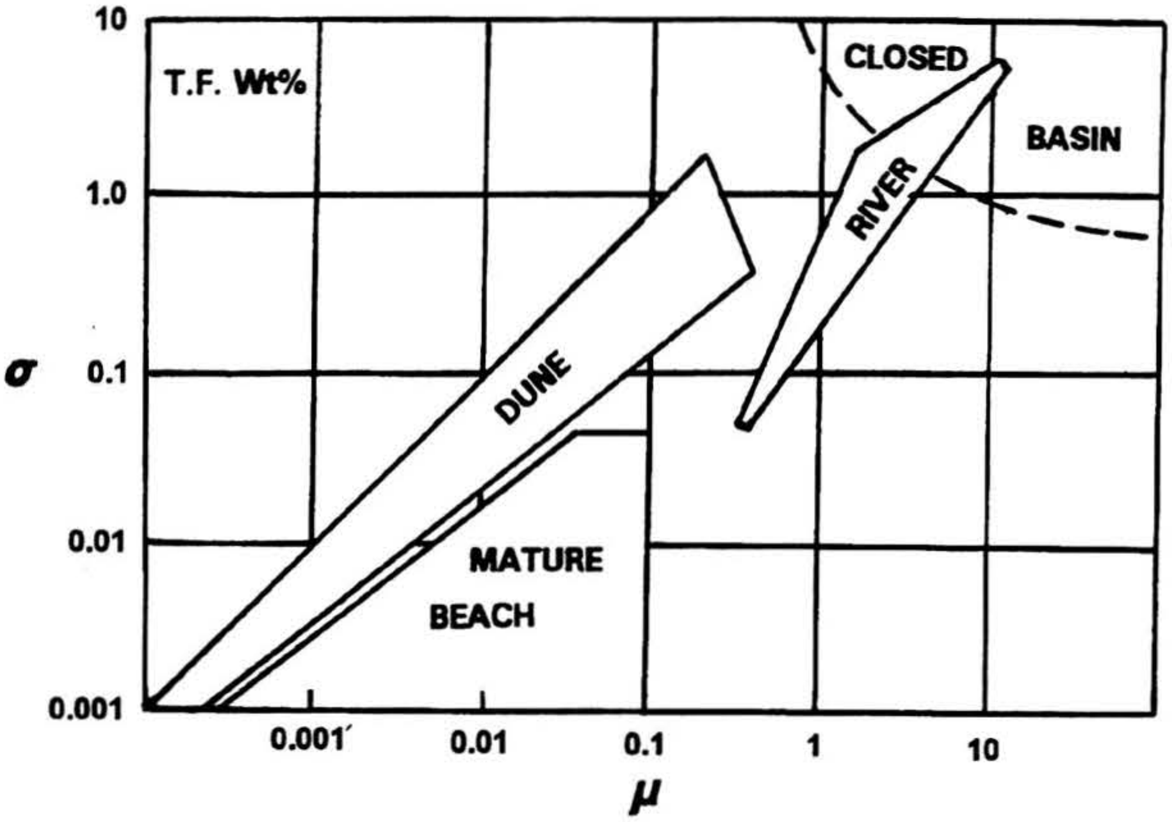
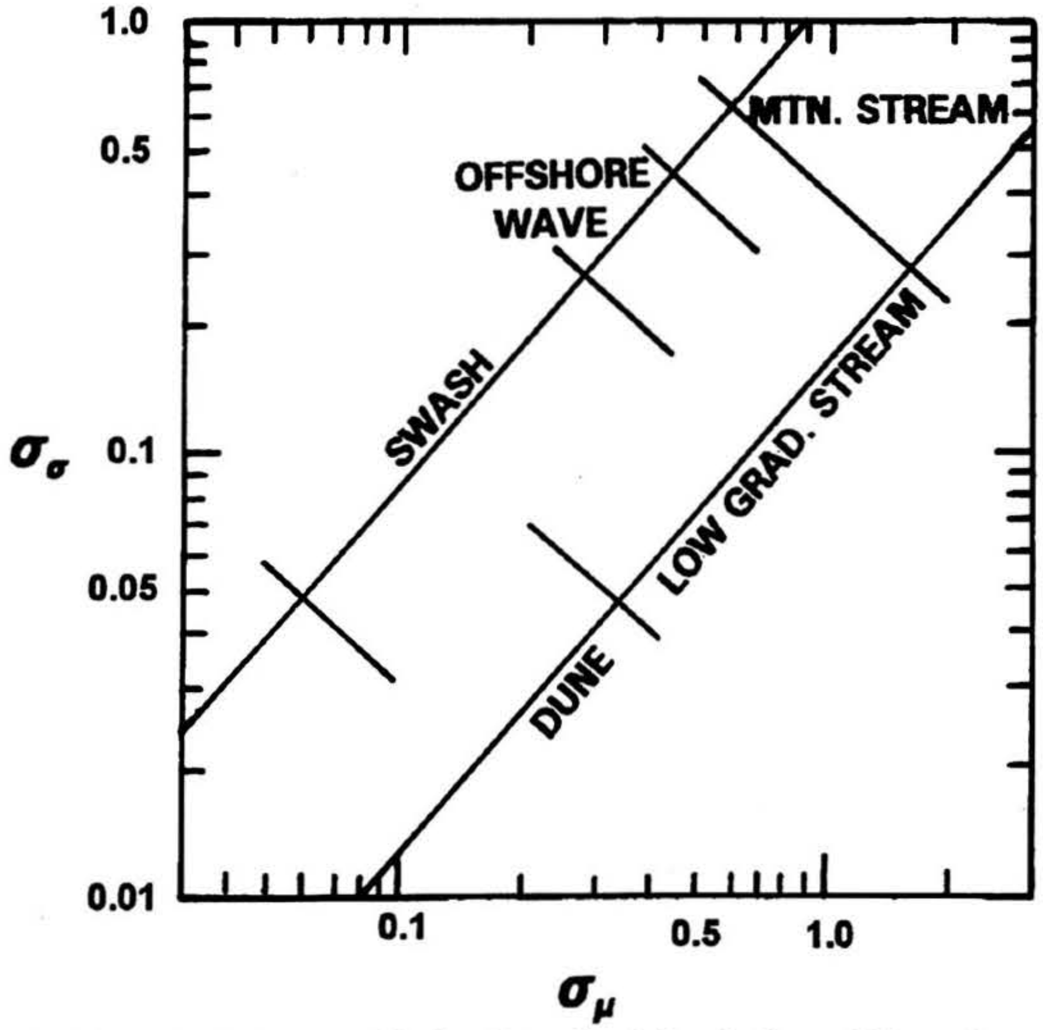
NOTES

Appendix IX

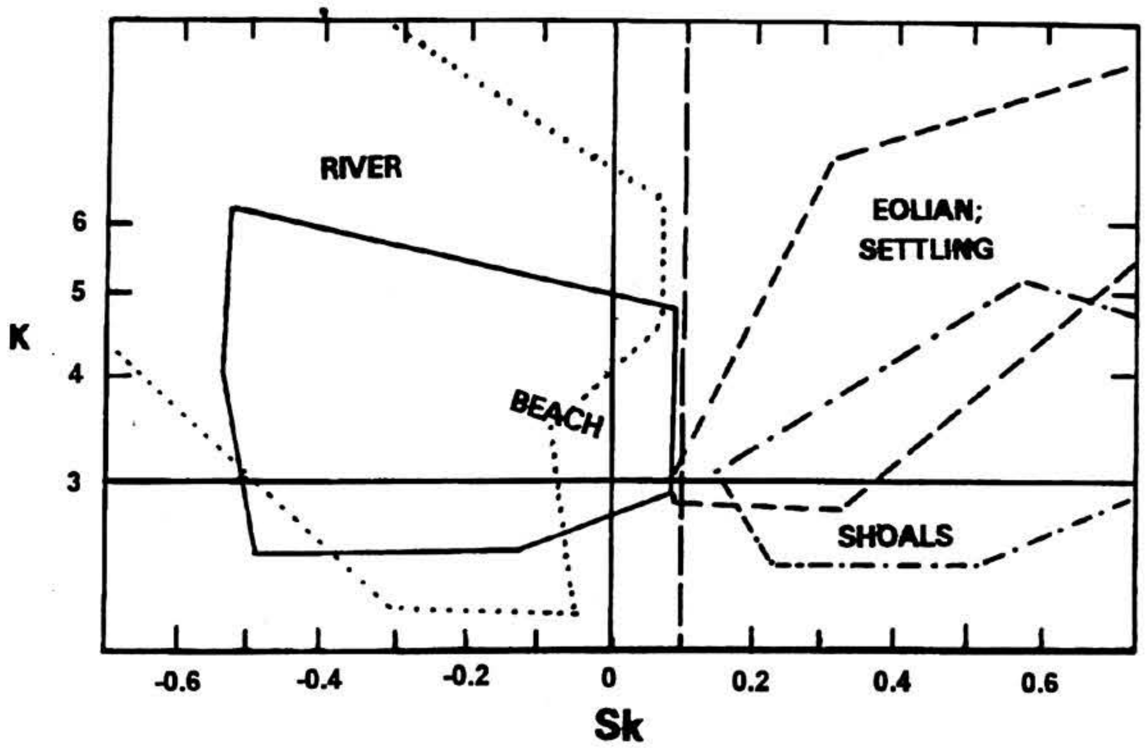
Sedimentologic Plotting Tools



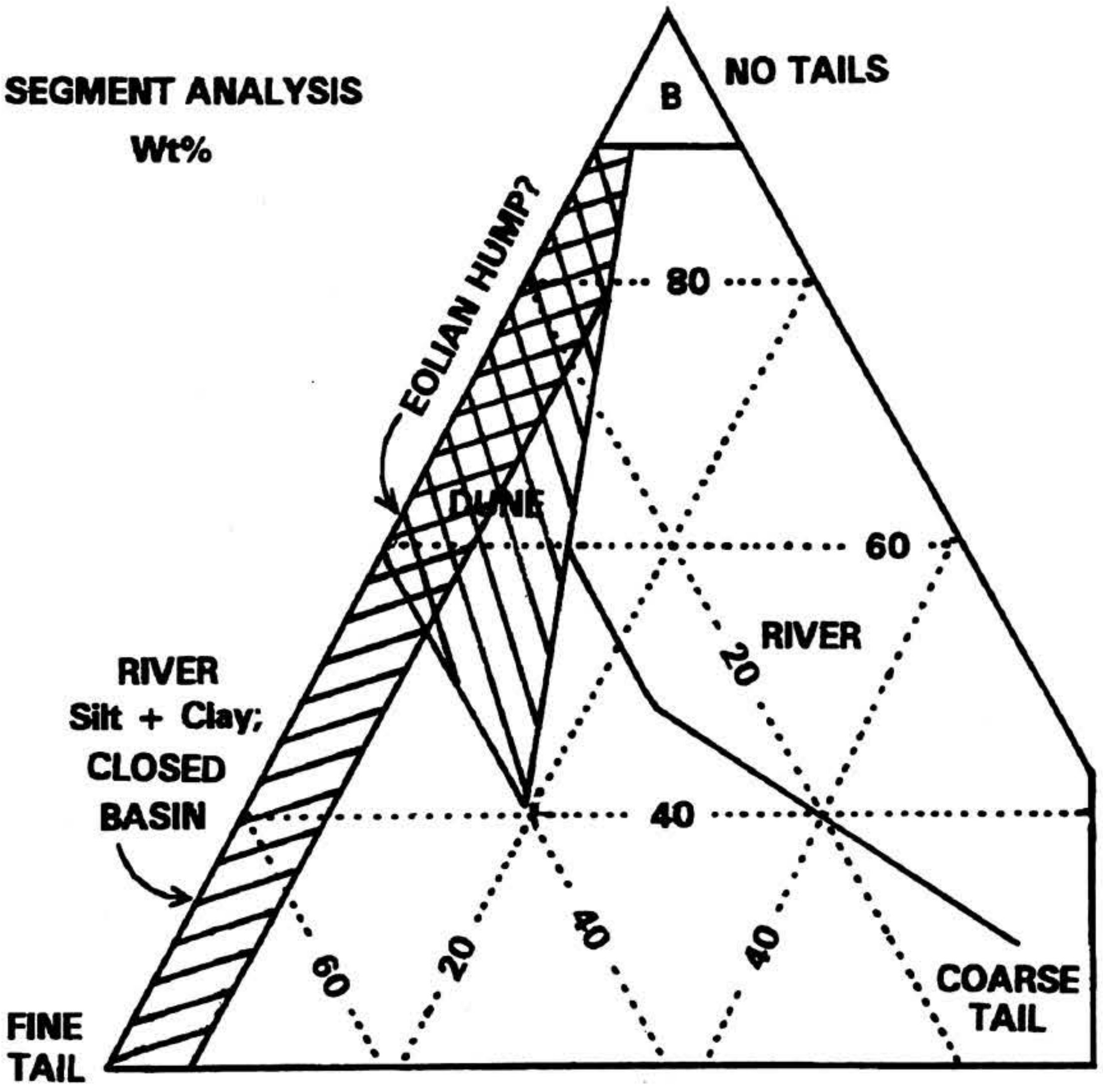
Tail-of-Fines Plot.



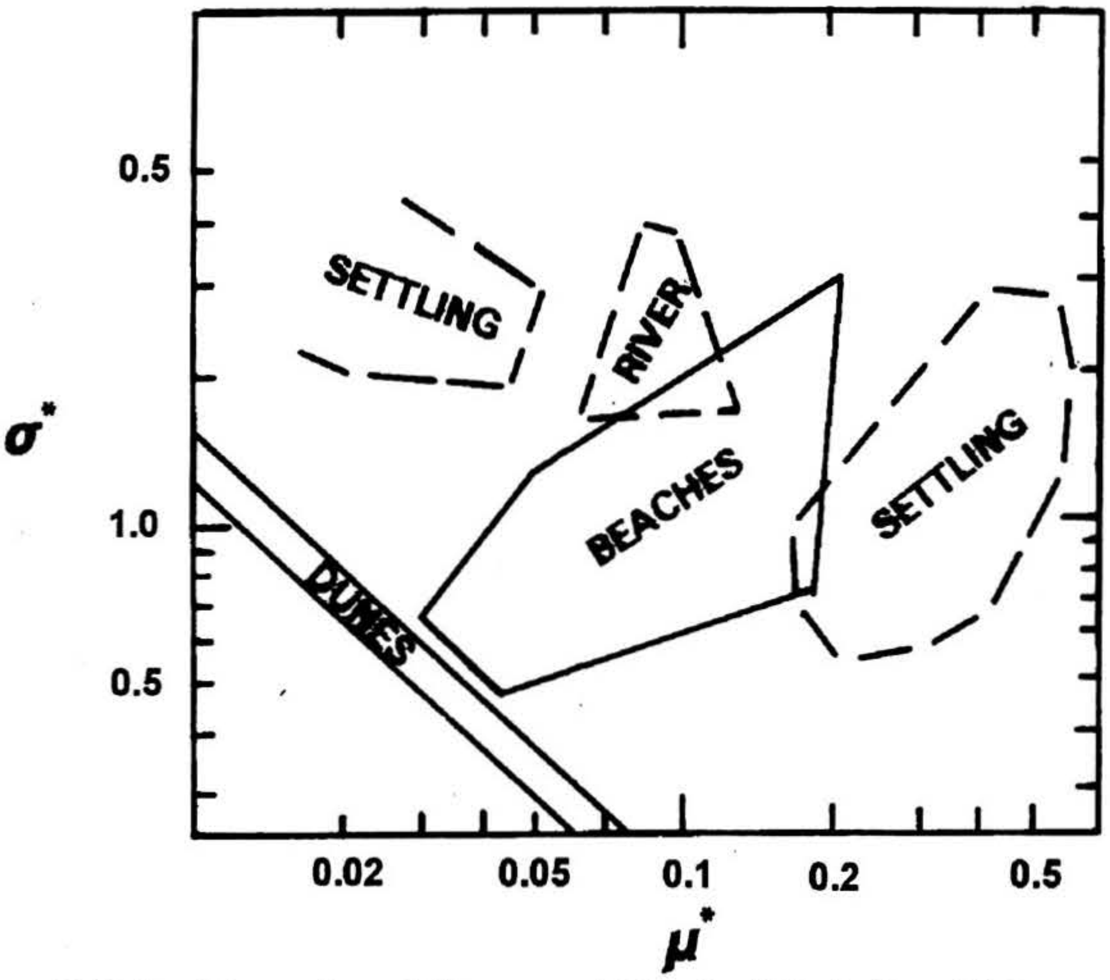
Variability Diagram (Suite Standard Deviation of Sample Means and Standard Deviations).



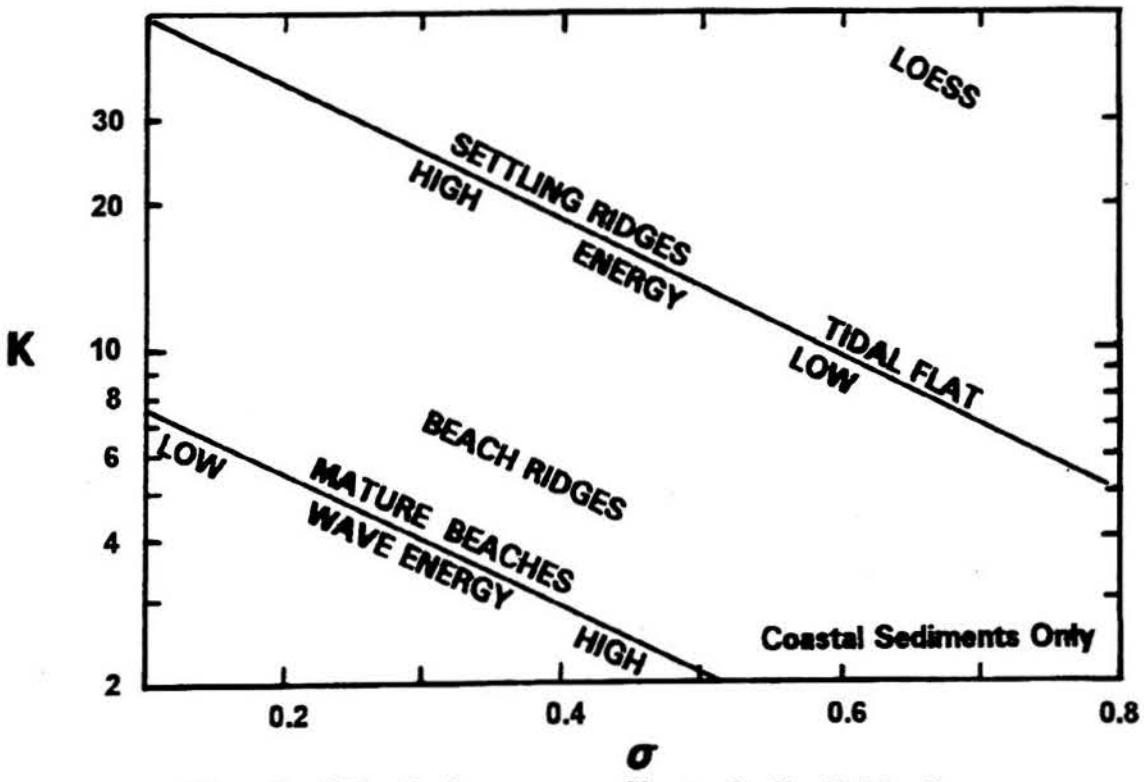
Skewness versus Kurtosis Plot (Suite Means).



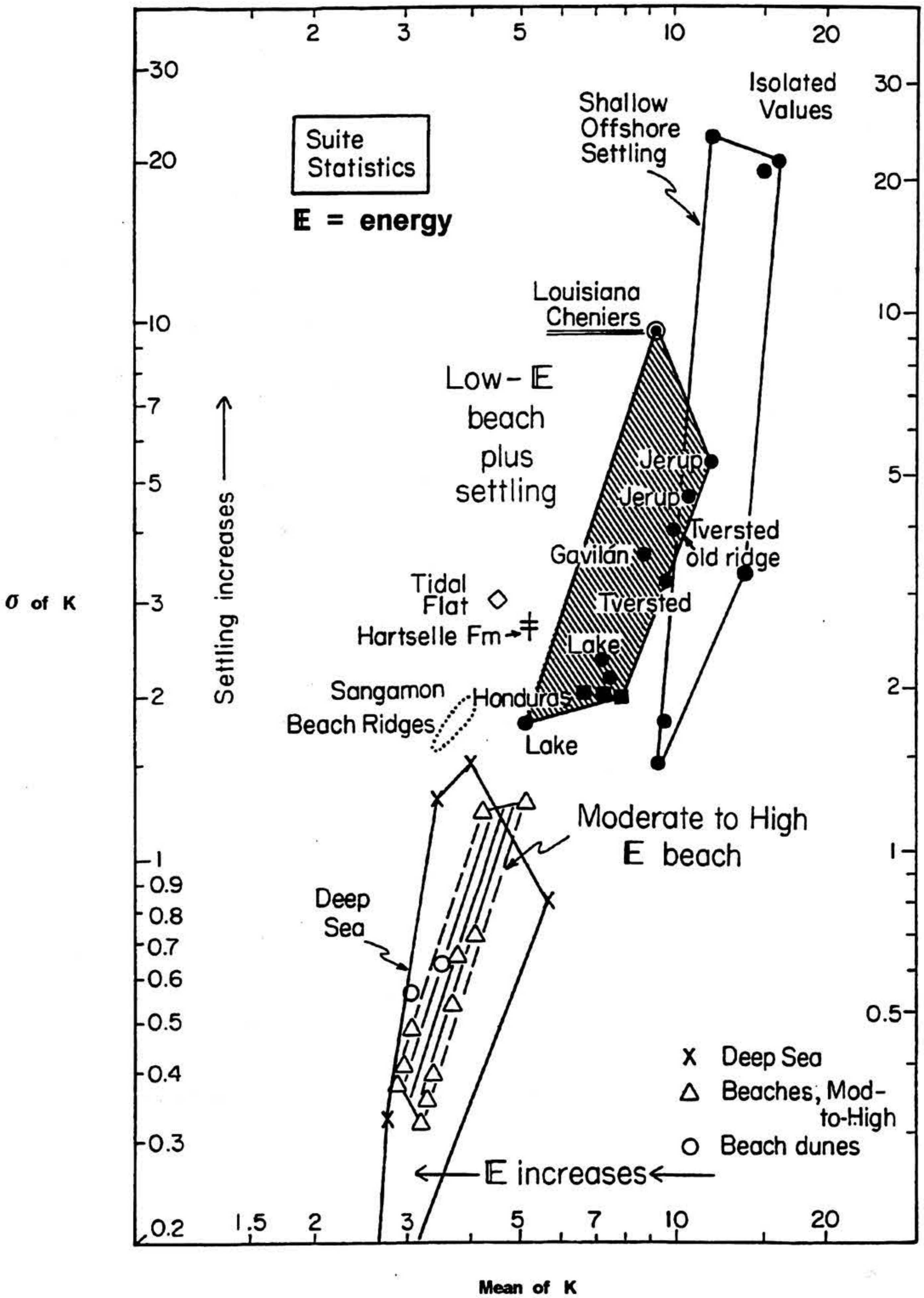
Segment Analysis Triangle.



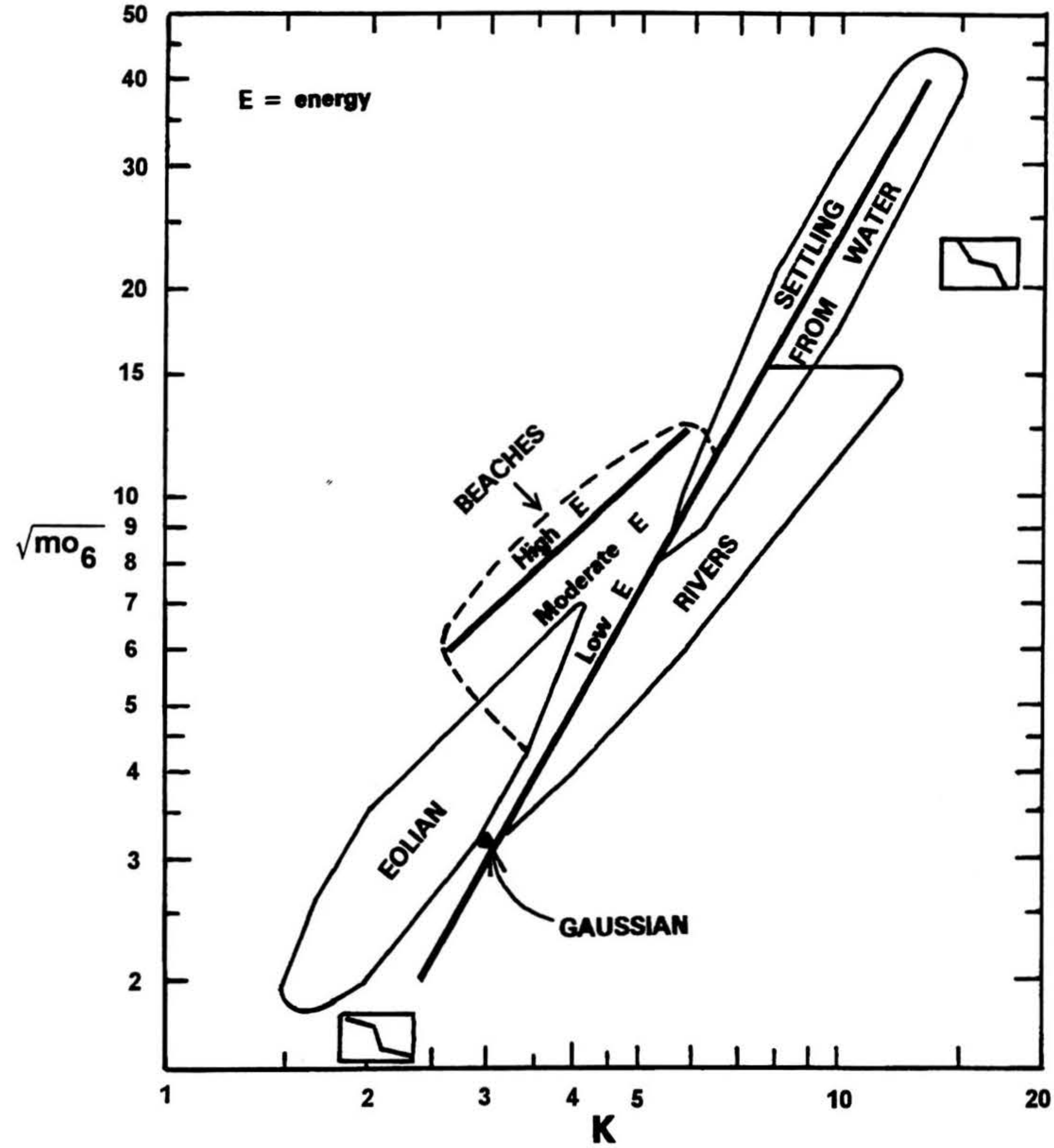
Relative Dispersion of Means and Standard Deviations Plot.



Standard Deviation versus Kurtosis (Individual Samples or Suite Statistics).



Standard Deviation of Kurtosis versus Mean of Kurtosis.



Kurtosis versus Square Root of the 6th Moment Measure (Suite Means).

Appendix X

Tanner, W. F., 1964, Modification of sediment size distributions: Journal of Sedimentary Petrology, v. 34, no. 1, p. 156-164.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 34, NO. 1, PP. 156–164
FIGS. 1–8, MARCH, 1964

MODIFICATION OF SEDIMENT SIZE DISTRIBUTIONS[1]

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ABSTRACT

Sediment size distributions commonly plot, on probability paper, as zig-zag lines. Nevertheless, the hypothesis that the basic distribution is normal (i.e., Gaussian) and will therefore plot as a straight line, is specifically retained. Possible modifications of the straight line plot include the following: simple mixing (adding of two or more basic components), censoring of a single component, truncation of a single component, filtering of a single component, or a combination of these. Simple mixing is the simplest, and therefore the one most likely to be successful in explaining zig-zag curves. Filtering is, in some ways, a negative version of mixing. An additional factor in the wide-spread appearance of zig-zag curves is the seemingly universal deficiency of certain sediment sizes (minima which separate gravel bed load, sand bed load, and wash load).

A variety of methods are available to the analyst who wishes to determine the "original" basic components in a given sample. These include a graphical method, and the method of finite differences. However, experience and intuition are more important than methodology in effecting a successful separation.

Bimodal distributions having a sharp inflection point near 2ϕ are conceivably the result of mixing sands from two different sources (such as a river, and wave erosion of standstone exposed on the near-shore shelf), or of transporting sands in the same area by two different agencies (water currents; wave motion). A possible sand dune history of sands such as this is examined and rejected. If the dual-transportation suggestion is correct, the 2ϕ "break" may be useful in interpreting environments of deposition of sands of the past.

The abundance of zig-zag curves, in sediment size distribution studies, makes clear the necessity for examining the detailed plot, rather than two or three statistical parameters (such as the mean and the standard deviation) which do not represent the zig-zag curve very well.

INTRODUCTION

The distribution of sediment particle diameters is generally reported, in the geologic literature, in terms of means and standard deviations. This practice is a tacit assumption that each sediment has a distribution of diameters which is, more or less, "normal" (or, alternatively, log-normal).

If the assumption were correct, most sediment size studies would plot on probability paper as straight lines. Many students of sediments have known, for some time, that this is not true.

If a size distribution plots, on probability paper, in some fashion other than a straight line, three problems arise:

1. What does this "non-normal" plot mean, in terms of physical characteristics of the sediment? (For example, do we have previously unsuspected hydrodynamic principles at work, or do grains of different sizes have different shapes and therefore behave differently, or are we dealing with mixed, or otherwise altered, sediments?)
2. Once a physical explanation of the non-normality is obtained, what does this explanation tell us in our efforts to reconstruct the environment in which the sediment accumulated?
3. What parameters can be used to characterize these non-normal distributions?

Bagnold (1941) observed that certain desert sands appear to be mixtures of two components. He used a semi-logarithmic plot in an effort to make these components separable. Doeglas (1946) studied departures from the normal law, concluded that many sediments are mixtures of two or three components, and proposed three basic components designated as the R, S and T distributions (fig. 1). More recently Doeglas (1955) has sought other methods of handling this general problem.

Tanner (1958) noted the well-known deficiencies of clastic sedimentary materials of certain sizes, and suggested that these deficiencies alone would require that many sediment distributions plot as zig-zag curves rather than as straight lines. The critical sizes are those between about 3ϕ and 4.5ϕ, and those between about 0.5ϕ and -3ϕ; these deficient sizes produce minima between more abundant sizes, which were labelled "gravel bed load," "sand bed load," and "wash load." Later (1959, 1960a, 1962a) Tanner outlined a method, using first and second finite differences, for attempting to separate components of a zig-zag distribution. He also suggested (Tanner, 1960b) that filtering, censorship, and truncation may be important, along with simple mixing, in combining components.

Curray (1960) attempted to trace sediment masses along the continental shelf of Texas and Louisiana by separating and identifying various

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[1] Manuscript received January 24, 1963.

modes within each sample. He was able to show that distinctive mixtures appear to maintain their identifying characteristics across tens or hundreds of miles of shelf. From this study, he identified four types, or modes: I, 0 to 2.9ϕ; II, 3.0 to 4.2ϕ; III, 4.3 to 7.1ϕ; and IV, smaller than 7.2ϕ.

Walger (1962) observed that single-layer sediment samples invariably show three normally-distributed components, each of which is sorted more efficiently (smaller dispersion, numerically) than the total layer sample, and that the latter is better sorted than a cross-section or channel type sample taken at the same locality. His plotted results show minima (deficiencies) in the vicinity of 3 or 4ϕ, 1 or 2ϕ, and -1ϕ; the present writer interprets these figures to mean modes in the granule, fine-to-medium sand, very fine sand, and silt size ranges.

Harris (1959) reported multi-component sands from beaches in Suez Canal Zone.

Fuller (1961) observed an inflection point near 2ϕ in shallow marine sand size distributions and wondered if this represents a "break" between the "impact law" and Stokes' settling velocity formula. He followed this up (Fuller, 1962) with a more detailed treatment, in which he considered the possibility that such samples have been wind-handled at some time in their recent history.

Van Liew (1962) has illustrated the graphical analysis of semilogarithmic plots, providing two or more straight-line components; this procedure does not appear to work for sediments.

Březina (personal communication) has proposed that Kapteyn's normalizing transformation can be used on *all* distributions, even the polymodal ones, thereby making them plot as straight lines. He has treated this procedure, in detail, for sediments which settled through still water. Application of his log-hydrodynamic transformation does not appreciably alter obvious cases of truncation, filtering, or mixing, but may be of value in more difficult cases, where still-water settling can be inferred.

PHILOSOPHY

It is certainly not known that a normal (or, log-normal) distribution is superior to any other available to the earth scientist (Middleton, 1962). The normal curve is actually a special case of a more general distribution, and it is not even known whether or not the latter is the most desirable one.

Additional investigation, however, must always be predicated on some general statement. Therefore, for purposes of study and contemplation, the following is offered: The normal distribution is adopted as the basic type; those curves which depart from the normal will be analyzed in an effort to categorize, in some way, the departures, and geological significance will then be sought in the various categories.

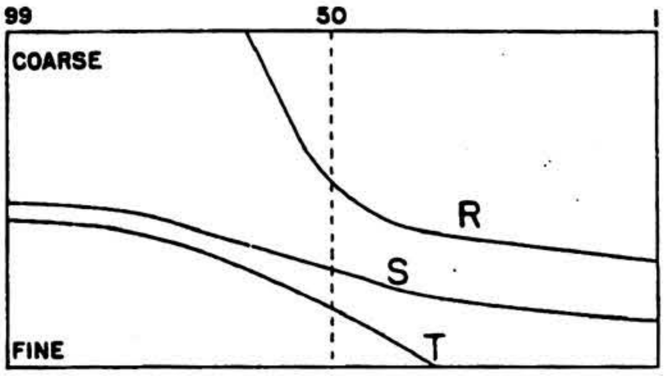

FIG. 1.—Three basic sediment size distribution types, according to Doeglas (1946).

This *modus operandi* will, it is thought, produce interesting and valuable results. It is conceivable that it may even aid in the whole business of clarification of the meaning of distribution curves in the earth sciences. It is, however, specifically contrary to the position taken by Friedman (1961, 1962).

SIMPLE MIXING

Following the early experimental work of Bagnold (1941), Doeglas (1946) developed the idea of mixing in relatively great detail. He designated three basic types, or curves, as R, S and T (fig. 1). R identified the "continuous current" depositional area, such as in a river or under a strong marine current. S was applied to currents having decreasing capacity in the down-stream direction, such as on the lee sides of dunes, river bars, shoals, and shallows. T was used to mean stagnant water conditions, and hence total deposition. Doelgas considered that many sands are combinations of two or more of these basic types: $R+S$, $S+T$, or $R+S+T$. It is true that, by combining these types, one can duplicate the size distributions of many modern sediments.

However, the present approach is somewhat different. We assume, here, that the Gaussian (or normal) distribution is basic, and then observe that each of Doeglas' three types can be obtained by proper treatment of a normal curve. In other words, we do not try to analyze a sediment curve in terms of R, S and T, which appear to be modifications of the assumed basic distribution, but rather we turn directly to "pure" normally-distributed components, in an attempt to see if the total sediment can be "explained" in this way.

Two (or more) normal distributions can be plotted on probability paper, and then "mixed"

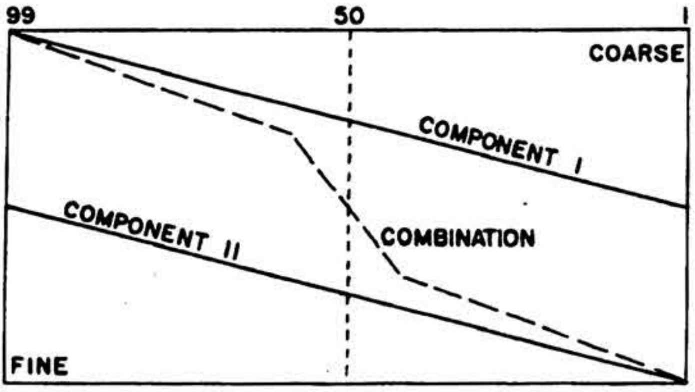

FIG.2.—Two components (I and II) having equal variances and proportions, but different means; and the combination obtained by simple mixing. Two inflection points appear.

(by simple addition) in any desired proportions. Doeglas presented examples of this process. Essenwanger (1960) has used the same idea in order to make rainfall analyses. The present writer has made many combinations of this kind on an electronic computer. Several things quickly become apparent.

If only two distributions are combined by simple addition, characteristic curves are obtained. These commonly have inflection points which can be located with an accuracy of about 5 percent (on the probability scale), or better. The inflection points typically indicate the proportions in which the components were combined. If both variances are essentially equal, the combined curve has three segments: two parallel lines, connected by a third segment having a steeper inclination (as plotted for the present paper) (fig. 2). If the variances are markedly unequal, the combination typically has two segments, one of which is sub-parallel to the dominant component, and the other of which is steeper than either component (fig. 3).

The inflection point may have a spurious, but nevertheless important, sharpness: where closely-spaced points are computed (i.e., at tenth-ϕ intervals) a sharp, but smooth, curve is produced; where widely-spaced (and hence realistic) points are computed, a definite inflection point is indicated. Inasmuch as sizing is generally done in whole-ϕ, half-ϕ, or quarter-ϕ units, curve mixing should, for practical purposes, be carried out in the same fashion. The inflection points which are so produced are artificial in one sense, but this is nevertheless what one obtains for real sediments.

The method of finite differences (Tanner, 1959, 1960a, 1962a) can be used in many instances to effect separation of two components. A graphical method has been quoted by Fuller (1961). M. Shimrat has devised a program for machine differentiation which might be applied to this problem. However, skill and experience often permit an analysis to be made when mechanical or rote methods fail. Regardless of the method, whether electronic, mathematical, or intuitive, a successful separation is achieved when the several components recombine to make the original distribution. There is no question of whether or not the separation is "correct." The only question remaining is, does it mean anything?

Three components are more difficult to detach than are two, four more difficult than three, and so on. Nevertheless, one example has been studied in which at least 10 distinctive components could be identified and (in this case) largely verified by non-statistical means. Examples having three, four, or five components appear to be fairly common, and in many instances relatively easy to manipulate.

Fuller (1962) considered a group of near-shore, shallow marine sand samples which have size distributions showing two segments. He observed that typical curves have two segments each, and an inflection point not far from 2ϕ. His plotted example looks like many similar two-component curves which the present writer has obtained either from sediments or by computer methods (such as fig. 3). Fuller examined two possibilities: (a) that the inflection is due to v change of hydrodynamic processes, at about 2ϕ, or (b) that the 2ϕ fraction was selectively removed by wind action at some time in the recent past when this sample was exposed along a beach. A third possibility should be emphasized also: (c) these samples are produced by simple mixing of two components having unlike variances. It is possible, of course, that the two different components might have been separated originally hydrodynamically, and hence Item (c) is closely related to Item (a). The second suggestion, that statistical selection of some kind was operative, is discussed under another heading.

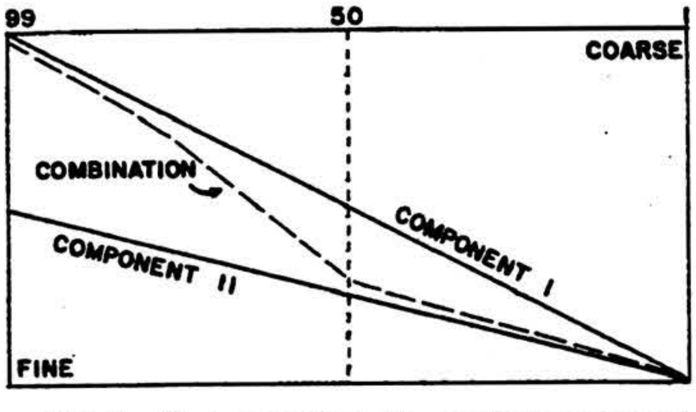

FIG. 3.—Two components (I and II) having equal proportions, but different means and variances; and the combination obtained by simple mixing. The single sharp inflection is at about 50 percent.

The published example (Fuller's fig. 1) shows, in analysis, one component having a mean of 1ϕ, contributing 3.75 percent, and a second component having a mean at 3.25ϕ, contributing 96.25 percent. The second more important component has much better sorting than the first.

If this is an example of simple mixing, how could the mixing have been accomplished? There are several possibilities: (1) a shelf area, fed by two streams, each of which delivers a sediment load having distinctive parameters, might show such mixing in various proportions; or (2) mixing might involve two components, one derived from stream flow, and one from wave erosion of sandstones exposed beneath the shelf waters; or (3) mixing might reflect two different hydrodynamic regimes. The sediment-transport diagram presented by Hjulström (1939) has three divisions: erosion, transportation, and deposition. Erosion, with minimum current velocities, is specified for sand-sized materials. Clay and gravel are shown as requiring higher velocities in order to put material into transit.

Hjulström's diagram was constructed for water currents, and particularly for rivers and canals. It might very well apply to shelf currents, also. But it probably does not hold for wave action. In the latter instance, stirring appears to be more important than lateral transport, and hence the three areas of the current diagram should be revised. This is equivalent to saying that minimum orbital velocities necessary to initiate transportation may not be adequate to maintain transportation, inasmuch as each bottom orbit does *not* operate with constant velocity, and furthermore the periodic reversal of direction should have the effect that sorting would be more efficient.

The proposal is made, therefore, that the minimum-velocity "erosion" area, for a wave version of Hjulström's diagram, be narrower, and to the finer side of the minimum velocity "erosion" area for the water current diagram (fig. 4).

If this concept is correct, a shelf area where both currents and waves operate effectively should be marked by bimodal sediments or negatively skewed sediments. The finer mode (wave-moved) should have better sorting, and the coarser mode (current-moved) should have poorer (numerically higher) sorting. The proportions in which the two components have been combined should be an indicator of the relative strengths of the two agencies.

Fuller's published plot could thus be interpreted as showing a water-current mode, 3.75 percent, and a wave-mode, 96.25 percent.

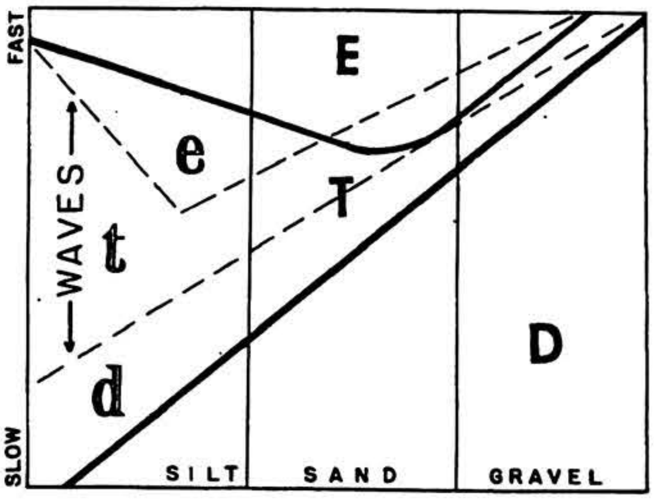

FIG. 4.—Hjulström's diagram showing erosion (*E*), transportation (*T*), and deposition (*D*), for currents (heavy lines), with possible processes for waves added (dashed lines).

Vause (1957, 1959) examined over 100 samples from the shallow shelf southwest of Tallahassee. All of these were taken one mile or farther from shore. Although they are commonly weakly bimodal, the secondary mode occurs in the fines. A significant secondary mode coarser than the primary component was not observed.

Waskom (1957, 1958) studied a suite of samples from the same general area. These were taken along the beach, from lagoons and marshes, and within the breaker zone. The breaker zone samples show strong bimodality, much like that of Fuller's published example. Inasmuch as Vause and Waskom were working in the same area, on different parts of the same sand sheet, one must conclude that the coarser secondary component is due to the operation of some marine process which is not effective in deeper water (i.e., 15 feet or more).

From bottom observations carried out by diving during the Vause and Waskom projects, it can be suggested that this difference is one of the following: (a) bottom currents are too weak, outside the breaker zone, to produce the secondary mode, or (b) breaking waves operate in some fashion unlike ordinary waves of oscillation. In either case, the secondary mode reported by Waskom was formed within, or very close to, the breaker zone, and did not appear in any other samples taken from a strip about ten miles wide on each side of the beach.

Brockman (1962) prepared analyses of a number of Upper Cretaceous sands from Alabama. These are largely bimodal. Their asymmetry must be taken to mean that the coarser, less important component is less well sorted than the finer, more important component. The present writer has held that much of the Cretaceous sedimentary section of Alabama is transitional or marine rather than continental (Tanner, 1955, 1962b). This conclusion was based on a comparison of cross-bedding directions with pinch-outs and truncations, as well as a consideration of how coastal currents *should* have moved if present concepts of Cretaceous wind and wave attack directions are correct. Brockman's study tends to support this conclusion.

CENSORSHIP

Simple mixing is not the only way of combining components. Three additional methods, described broadly as "statistical selection" are censorship, truncation, and filtering. Mason and Folk (1958) have used the term "amputation" for one or more of the various selection processes.

Censoring involves the suppression of all of the information of one variety, concerning the sample with a certain range of values. The missing information normally belongs to one or both tails, but in some instances might be taken from the middle. There are two types of censorship: Type I, where the number of suppressed classes is known, and Type II, where the number of suppressed measurements is known. In Type I censorship, the investigator does not know what numerical values are to be assigned to the suppressed classes. In Type II censorship, the numerical values to be assigned to the individual items (i.e., diameters) are not known.

Many sediment curves published in the literature show single censorship; that is, information as to the nature of the distribution, below the finest screen size, is not conveyed, but the total amount of sediment, within that part of the distribution, is nevertheless known (it was caught in the pan). This is Type II censoring: the number of suppressed classes is not known, but the total number of items from all of these suppressed classes is available. The analyst has no difficulty in working with the distribution so obtained. The necessary statistical parameters can be computed sufficiently accurately, or can be estimated directly from the probability plot. If no other modifications were made, the plot shows a single straight line.

Censoring is the mildest form of selection. In some instances, more than 50 percent of the total sample can be missing without impeding analysis providing the assumption of true normality can be made. Even if the missing portion of the sample is the middle 50 percent, the original distribution can be reconstructed. Precise numerical methods (to any desired degree of precision) are available for use with censored samples (Cohen, 1955, 1957, 1959, 1960).

The censored distribution calls no special attention to itself, inasmuch as it looks like the ordinary distribution. It therefore requires no special explanation.

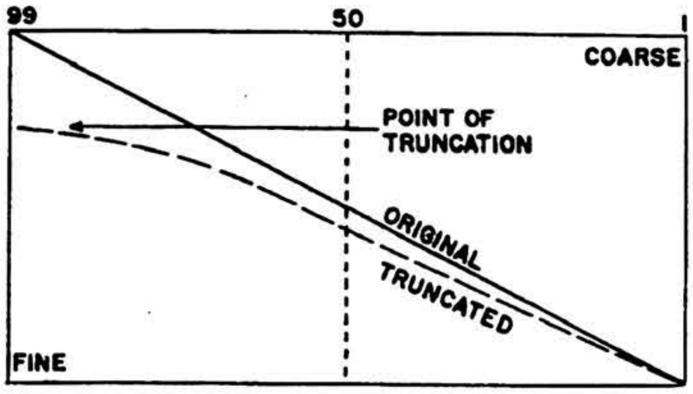

FIG. 5.—Single truncation.

TRUNCATION

Truncation involves the total removal of a continuous set of values from part of the distribution. This generally occurs in one or both of the tails. No information is available as to either the number of missing classes *or* the number of missing items. For this reason, truncation is a more severe form of selection than is censorship. A truncated sample would occur if, for some reason, all of the sediment passing through the finest screen into the pan were thrown away or lost, and if the total weight had to be determined by summing the weights of the material coming to rest on the several screens. Under such circumstances, one would not know the total original weight, the percentage of weight caught in the pan, or the diameter of the smallest size. A curve plotted from these data would be much more difficult to handle, although it should be fairly obvious that truncation had taken place.

Sediments which have been subjected to truncation show size distribution plots which typically are smooth, gentle curves on probability paper. No inflection points are present unless other modifications have also taken place. The truncated tail has better "local sorting" than the other tail; that is, the truncated tail plots as a flat, or nearly horizontal, segment, rather than as a steep line (as shown in the accompanying graphs; figs. 5, 6).

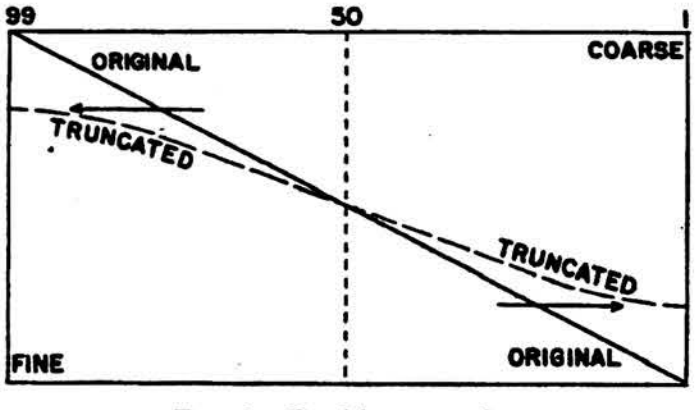

FIG. 6.—Double truncation.

A doubly-truncated distribution appears at first glance much like a plot made by combining two components having similar variances: two flat tails connected by a steeper middle segment. The bimodal plot, however has inflection points (typically), whereas the doubly truncated plot does not.

The *R* and *T* types of Doeglas look like singly-truncated curves. He later adopted the "truncation" terminology (Doeglas, 1955). The *T* plot, representing stagnant water and total deposition, looks as though the coarse fraction were missing. This is logical, inasmuch as the coarse fraction probably could not have been introduced into truly stagnant water. The *R* plot, representing steady currents (such as in rivers) looks as though the fine fraction were missing. This is also logical, inasmuch as the finest materials should not settle out in strong currents.

The *S* type of Doeglas looks like a doubly-truncated curve. Both coarse and fine fractions appear to be missing.

The statistical literature is not as helpful, with regard to truncation, as it is in connection with censorship. That is because of the inherently greater difficulties in the case. A censored sediment curve looks quite ordinary: in actual practice, the analyst makes the necessary adjustments more or less automatically. A severely truncated curve, however, looks quite strange, and trial-and-error manipulation may be required in any effort to approximate the original. A beginning has been made, however, with truncated data (Cohen, 1955, 1957, 1959, 1960).

FILTERING

The two previous forms of selection affected continuous ranges of values. Filtering is a more drastic modification, in which the suppressed items were not necessarily a continuous part of the original measure spectrum. This can be visualized by thinking of a capricious geologist, who toys with the sediment after the sieving is complete, but before weighings have been made. He removes various amounts of sediment from each of several sieves. When he is through, the total original weight cannot be determined, and the analyst does not know what pattern was used, if any, in making his alterations. The pattern, of course, has a statistical distribution of its own, and this is completely unknown.

Two kinds of filtering can be distinguished. In simple filtering, the missing data have been suppressed according to some specific (but unknown) pattern. In some instances, the filter may be influenced by the original sample, so that both components are altered, each by the other; the result is mutual filtering.

Quartz-and-carbonate sands may owe part of their character to a filtering process. The total sample may produce a single straight line plot. Separation into two components by hand may produce two straight line plots. Yet removal of the carbonate by leaching with acid may produce a bimodal curve. In the latter instance, fine insoluble grains, formerly masked because they had been incorporated within the shells or shell fragments, now appear in the quartz component. These grains were removed from an original sample by organic filtering (the animal which secreted the shell appropriated them from among whatever other sizes may have been present). The final "insoluble" component is really a mixture containing the true quartz fraction plus a fine fraction which, as far as natural hydrodynamic processes are concerned, was added in the laboratory.

Experience with filtered distributions is, to date, inadequate for rules to be laid down. The literature offers essentially no guidance; the problem is inherently exceedingly difficult. It may not even be possible to recognize harshly filtered distributions. Nevertheless, analysis of samples must proceed; hence it may be simpler to reject the hypothesis of filtering, sample by sample, unless strong evidence to the contrary, either statistical or geological, can be adduced.

NATURAL SELECTION

The simplest procedure which will yield acceptable results is probably the best procedure. Therefore a workable program might be to ignore the effects of censorship (which does not, generally, alter the appearance of a curve), to reject the hypothesis of filtering (unless other evidence is available), and to attempt to distinguish, by inspection, between the results of truncation and simple mixing. Inasmuch as the two processes commonly produce quite different distributions, this should not be too difficult. Once a decision has been made, the task of resolving the components can be undertaken. This will include the identification of points and agencies of truncation, if present.

Fuller suggested that his bimodal shelf sands might have acquired their zig-zag distribution as a result of removal of certain sizes by wind action. He postulated that the suppressed, or reduced, classes were those near the middle of the distribution. The number of affected classes is unknown, the total amount of information removed is unknown, and there are no data regarding the continuity of the missing sizes. The "wind removal" hypothesis is, then, a suggestion that a single original sample has been filtered (by a specific agency: wind). This is, of course, a very real possibility. It might be rejected on the grounds that the distribution can be explained,

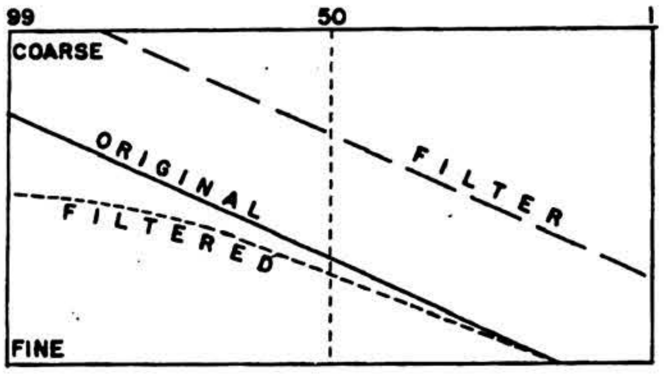

FIG. 7.—Filtered distribution, where the filter mean is larger than (i.e., coarser than, in terms of grain size), and the filter variance is equal to, the comparable parameters of the main component.

adequately, by assuming simple mixing, and therefore we have no need of the more difficult hypothesis of filtering.

Intead, it may be more profitable to examine the notion of filtering by wind to see what results might be obtained in this manner.

The most obvious gap in reconstructing a filtered distribution is a knowledge of the character of the filter. This same gap, however, occurs in many other instances, where the analyst is not particularly annoyed by the fact that he doesn't really know what kind of a distribution he is studying. Therefore, it should be almost a matter of routine to assume that the filter has a normal (Gaussian) distribution, and that a normally-distributed filter can be treated as if a *negative* component were being added to the primary component. By means of this assumption, filtering can be handled by the same methods which are used in separating simple mixtures. Application of this procedure can be done in three different ways; in each instance the filter is assumed to have a mean of about 2ϕ (following the suggestion of Fuller).

The possibilities are these:

(1) Filter variance is numerically greater than sample variance, and the filter mean is equal, or close, to the sample mean. This has the effect of eliminating sample tails, thereby reducing the sample variance. No zig-zag curve is produced.

(2) Filter variance is numerically equal to sample variance. This produces a result which looks like a singly-truncated distribution: straight in one tail, and curved in the other. If the filter mean is coarser than the sample mean, the apparent truncation will appear in the coarser tail of the sample (fig. 7), and positive phi skewness appears. If the filter mean is finer, negative phi skewness is obtained.

(3) Filter variance is numerically smaller than sample variance. If the filter is strong enough to have any appreciable effect, the result is a curve which is more complex than any discussed previously in the present paper, with perhaps four segments, or at least two straight segments plus one arc (fig. 8).

Fuller's published example does not match any one of the three possibilities. The wind-blown sand described in his Figure 2 has essentially the same variance as his main sample. Filtering by this mechanism should produce the results of Example No. 2 above; instead, it yields a two-segment inflected line. The conclusion which must be drawn is that application of a normally-distributed filter, through wind action, is not warranted.

The hypothesis of simple mixing (that is, the adding of one component to another) is therefore adopted for this marine, near-shore sample. Several suggestions to account for simple mixing were advanced in another paragraph (two rivers as sediment sources; a river plus wave erosion of the sea floor as sediment sources; water-current action and wave action as two different transporting mechanisms). It should be possible by examination of other samples from the same shelf area to determine which of these is the preferred explanation.

CHARACTERIZATION

Three questions were posed in the introduction. Tentative answers for the first and second have been expressed in the preceding paragraphs. The third question was: How do we characterize these non-normal distributions? Until more sophisticated procedures are available, the most direct method is to specify the mean and standard deviation of the total sample, plus the mean, standard deviation, and percentage of each com-

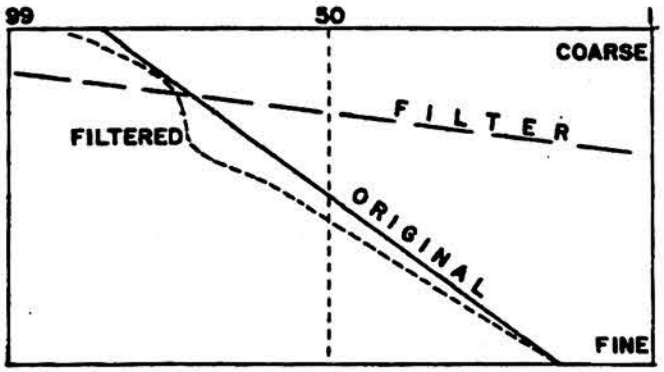

FIG. 8.—Filtered distribution, where the filter mean is larger (i.e., coarser, in terms of grain size), and the filter variance is smaller, than comparable parameters of the main component.

ponent, plus the method of combination or modification which appears to have operated.

CONCLUSIONS

The notion that sediment size distributions are essentially normal (Gaussian) is adopted as a working hypothesis. On the basis of this concept, zig-zag curves are considered to be combinations or modifications of ordinary normal distributions. It is observed that several operations are available, whereby straight-line normal components can be altered to match observed sediment distributions: simple mixing, truncation, and filtering. Filtering is, in some respects, an operation much like simple mixing (adding). (Censoring does not appear to alter a sample plot.)

Various methods can be used in the analysis of zig-zag curves. Some of these are graphical, some are arithmetic (method of differences), and some are primarily a combination of experience and intuition. A surprisingly large number of examples yield to one or more of these methods, despite the apparently insurmountable mathematical difficulties which seem to be inherent in the basic problem.

Bimodal shallow shelf sands are possibly the result of mixing of sediment from two different sources, or of mixing sediment carried by two different agencies (waves; currents). If the second of these two suggestions is borne out by later experience, an additional tool will be made available for interpreting some of the sands of the past. Deflation of selected sizes from beaches is rejected, at least for the present, as a means of obtaining a sharply-inflected plot.

Continuing study of sediment size distributions makes even clearer the necessity for examining the detailed size plot, rather than relying on a handful of elementary parameters, such as the median and standard deviation, which mask about as much information as they reveal.

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