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MULTIVARIATE ANALYSIS OF A SEDIMENTARY ROCK FOR EVALUATING EFFECTS OF SEDIMENTATION PROCESSES

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ABSTRACT. Patterns of variation in the spatial arrangement of compositional and textural properties of a rock reflect the effects of interacting natural processes. A model containing four independent processes (provenance, erosion-transportation, deposition, and diagenesis) is considered as a framework for interpreting covariation in the rock properties.

The data comprise 240 quantitative estimates of proportions of quartz, feldspar, lithic fragments, matrix, and mica as well as grain size, sorting, shape direction, and perfection of grain orientation in two perpendicular planes of a core sample of low rank graywacke.

Factoring (R-type) of the correlation matrix followed by its varimax rotation yields the following factor pattern.

Grain size and size sorting are most strongly correlated with the first two factors, of which the first appears to represent effects attributable to "competence of the transportational-depositional medium", and the second to "variation in or range of energy in the depositional environment". Grain size is thus independent of size-sorting, and both factors account for 33 percent of the total petrographic variability.

Variation in quartz proportion dominates the third factor, feldspar and mica the fourth. The association of lithic fragments and matrix on the fifth factor implies a detrital rather than authigenic origin for the intergranular material. These three factors are collectively identified with independent effects of the "source area".

Grain orientation dominates factor six while grain shape and perfection of orientation appear strongly in factor seven, reflecting some "aspect of current direction" during deposition.

These seven components account for 85 percent of the petrographic variation in the rock, suggesting that the four component model is overly simple. Also, the predominance of the effects of hydraulic influences suggests that variables measured on the rock properties carry little specific information related to original source area of the material.

Interpretation of sedimentary rocks in terms of factors representing the underlying influences of sedimentation processes should allow them to be classified into more genetically meaningful groups than schemes based on variation in raw properties.

INTRODUCTION

Variability in the spatial arrangement and distribution of the compositional and textural elements of a sedimentary rock reflects the differential influences of underlying natural processes. The final product, the rock as a structural entity, therefore represents the sum total of the effects of all processes that have tended to operate on its constituents during various phases of its evolution or petrogenesis.

Problems in sedimentary geology often require the unravelling of the history of a sedimentary rock in order to describe specific aspects of

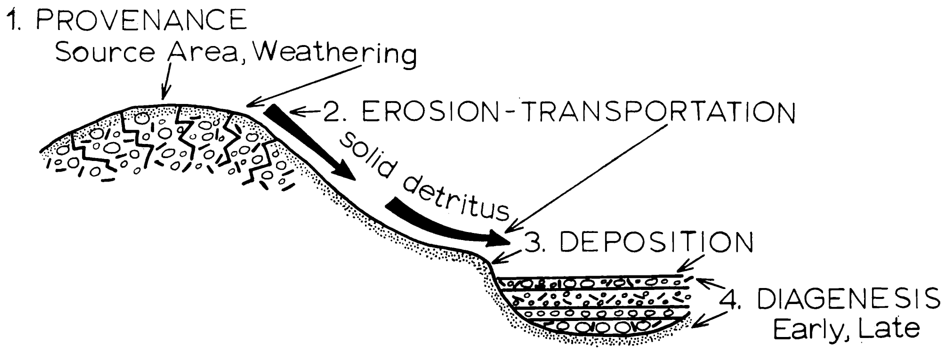

Fig. 1. Four basic processes in the petrogenesis of a detrital sedimentary rock (after Krynine, 1948).

its early formational stages. To accomplish this, the effects of all the subsequent processes whose influences are manifested in the petrographic properties of the rock itself must be "stripped away" in order to characterize the phase concerned. To achieve this, it is first necessary to define the rock in terms of the basic processes that have evolved it, then remove the effects of the unwanted processes to focus on any particular one.

Four basic steps may be conceptualized as:

1. Provenance: initial state of the material reflecting the nature of source area and degree of weathering where the sediment originates.
2. Erosion and transportation: process involving the movement of the material (usually by hydraulic means) to its place of final deposition.
3. Deposition: process by which the material "settles out" from the transporting medium (usually in an aqueous environment).
4. Diagenesis: process of subsequent alteration of the deposited material in response to changes in the physico-chemical environment.

The existence of an almost infinite number of additional (hopefully minor) processes cannot be ruled out. These described above are merely four "semantically designated", conceptually definable, easily visualizable phases. The relationships of these processes in the petrogenesis of a detrital sedimentary rock as visualized by Krynine (1948) are illustrated in figure 1.

Conceptually, these phases are independent. For example, the mineral composition of the source area is unrelated to the erosion-transportation phase which is determined by type of medium, its strength, competence, the duration over which it operates (in both time and distance), et cetera. Diagenesis as a process is likewise independent of the source area as it is primarily a function of environment with respect to temperature, pressure, and chemistry.

It is by evaluation of the patterns of covariation displayed by variables measuring the petrographic properties of the rock that the effects of underlying processes are defined. The task of evaluating these effects would be indeed simple if each process were reflected by one mutually exclusive set of rock properties, such as illustrated schematically in figure 2.

In the case of the common, measurable properties of sedimentary rocks, however, each single property will have some proportion of its variability accounted for by other influences (or the effects of additional processes). This case is illustrated in figure 3, where it is noted, for example, that the petrographic variables feldspar, mica, and matrix proportions are located in the zone denoting the intersection of the sets "P", "E-T", "D", and "Di" which represent the four original processes. The open circles represent theoretical properties (at present unknown). If these were definable and measurable, they would provide effective estimators since the sets representing the four conceptual processes become mutually exclusive when defined as functions of these variables.

It is of course possible that the converse situation holds, that is, the commonly measured properties (filled-in circles) also constitute elements of mutually exclusive sets representing the effects of unique processes entirely different from the four conceptualized in this work. Also, some degree of overlap in the process sets will occur due to covariation in the properties induced by measurement technique as well as experimental error.

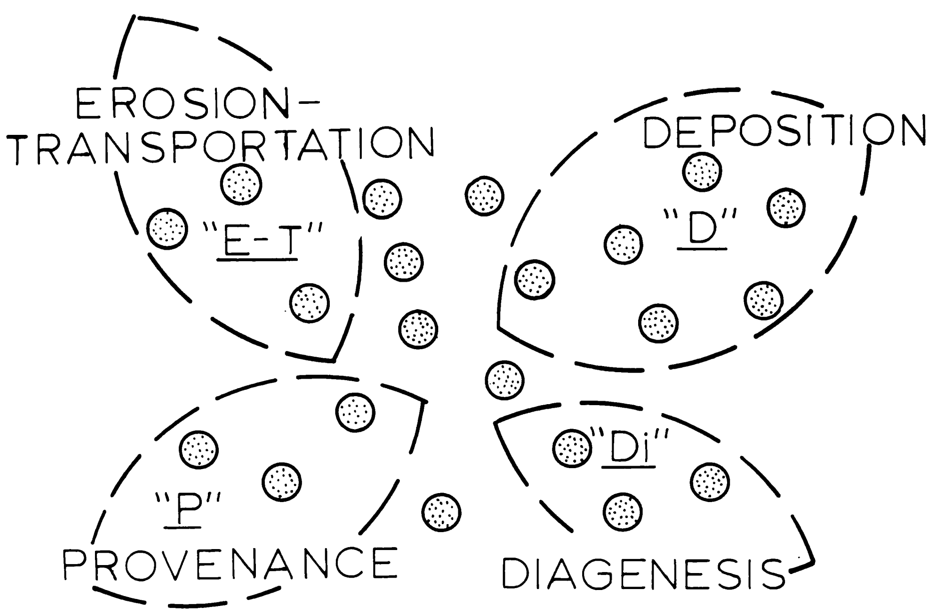

Fig. 2. Conceptualized independent sedimentation processes, the effects of which are theoretically defined by mutually exclusive sets of petrographic properties.

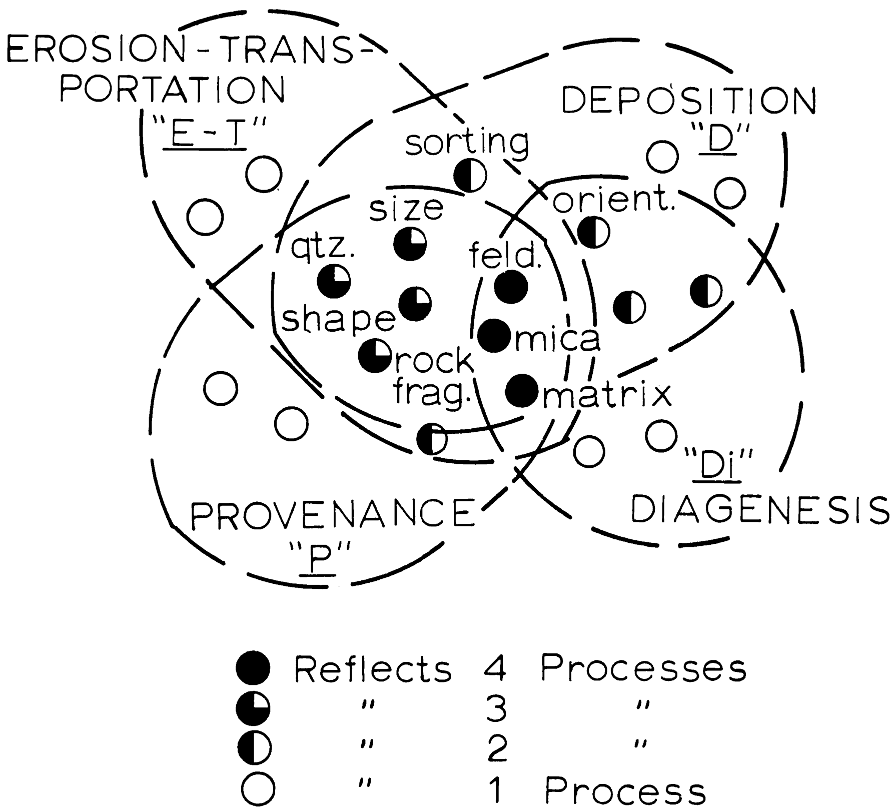

Fig. 3. Relationship among sets which represent processes, and the properties which reflect their effects.

OBJECTIVE

The objective of this investigation is to define the patterns of covariability displayed by a number of petrographic properties related to the compositional and textural characteristics of a sample of low rank graywacke (Krynine, 1948) in order to identify with processes the underlying factors which have operated during petrogenesis. Analysis (univariate) of trends in the petrographic properties considered individually is presented by Dahlberg (1965) and Dahlberg and Griffiths (in press).

METHOD

Two orthogonal planes cut perpendicular to the plane of the bedding in a core sample were subsampled according to the scheme in figure 4. Thin sections in these two planes were further subdivided giving 240 cells and quantitative measurements made on the compositional variables (proportions of) quartz, feldspar, rock fragments, matrix (clay), and mica. The textural properties estimated were quartz grain size (a and b axes transformed to phi units), size sorting, grain shape (ratio of b-axis to a-axis), mean grain orientation, and spread in orientation. A number of these properties are illustrated in figure 5. A marked difference between the sediment in the upper left corner and that in the lower right is depicted. While it is obviously textural, it is at the same time compositional. The ambiguity involved in interpreting such a difference in terms of provenance, transportation, depositional environment, and diagenesis is apparent. The lack of a unique solution in terms of these measured properties is obvious from the relationships illustrated in figure 3, where these variables are seen to lie in the intersections of the sets. Thus each reflects some portion of several processes.

ANALYSIS

Multivariate techniques including factor analysis provide an effective method for evaluating underlying influences whose effects are mani-

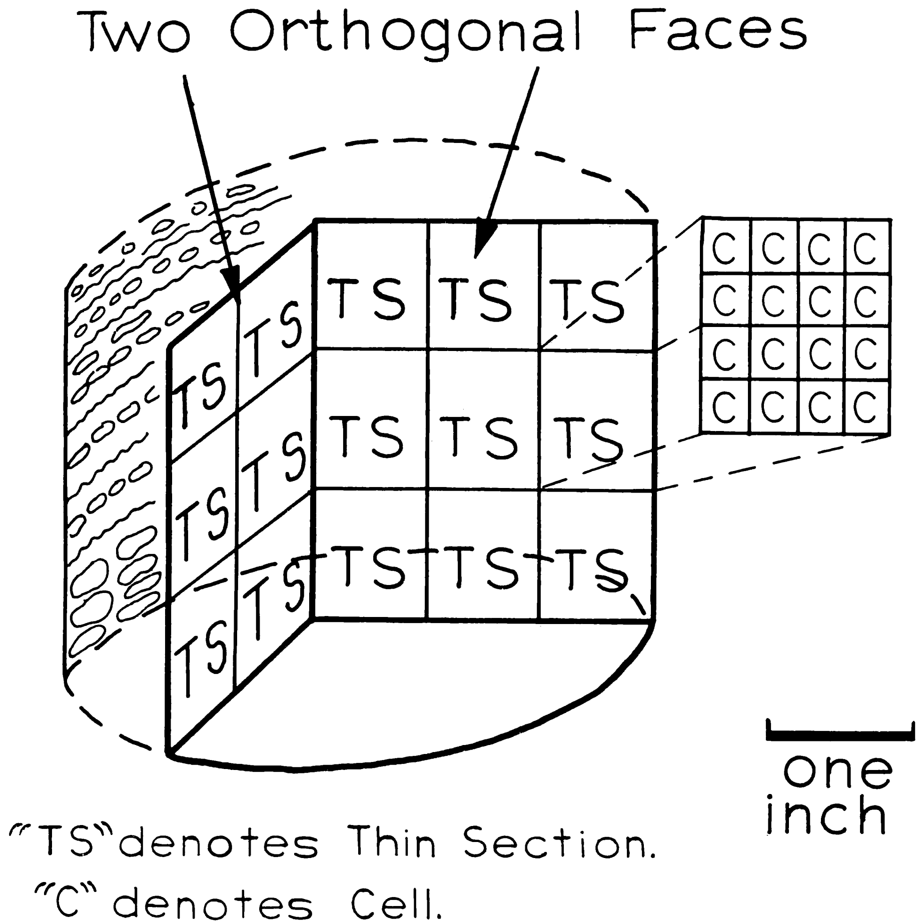

Fig. 4. Sampling scheme and rock specimen.

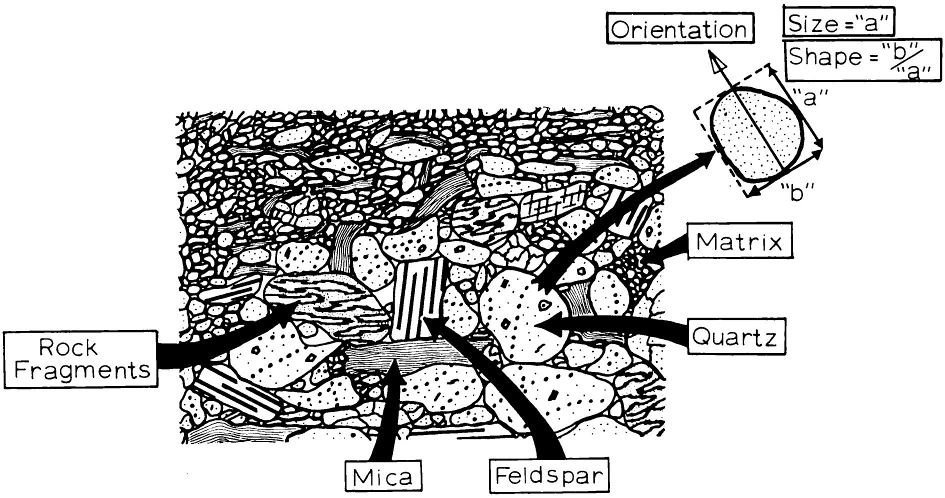

Fig. 5. Petrographic properties upon which the variables were measured as viewed in thin section.

fested in the relationships observed (or patterns of variation existing) among a number of interacting measurable properties. The theory and methodology is presented by Kendall (1957) and Cattell (1965).

With a few notable exceptions, factor and principal components analysis have largely been applied in the geological sciences to problems of classification (that is, using the Q mode which considers samples across all properties) rather than to identification of underlying hypothetical entities. See, for example, Imbrie and Van Andel (1964) and Klovan (1966). Factor analysis in the R-mode deals with the interrelationships among the properties across the samples.

Griffiths and Smith (1964) have used component analysis for resolving the most efficient set of axial measurements for defining the shapes of pebbles, and Griffiths (1966) describes the value of coupling both types of analysis in deriving genetic theories concerning sedimentary phenomena.

Proceeding with the matrix of observations (240 x 12), the correlation matrix (12 x 12) was computed and is shown in table 1. The statistically significant linear interrelationships among all pairs of variables are shown. The correlation between grain size and most of the compositional properties is notable. Size sorting is independent of all of the compositional properties. Grain shape is related to degree of perfection of orientation (as the grains become more oblong, they become more homogeneously oriented), while the orientation direction is independent of all other properties.

To determine a set of underlying influences whose effects are represented by the observed patterns of covariation among these variables, the

TABLE 1

Simplified matrix of correlation coefficients greater than 0.1

	Properties	mica	rock fragment	feldspar	quartz	"a" size	"a" sorting	"b" size	"b" sorting	shape	direction of orientation	perfection of orientation
		Composition				Texture						
Composition	matrix	....	–0.4	–0.2	–0.4	0.4	....	0.4	....	....	....	....
	mica	1	–0.3	–0.3	....	....	....	0.2	....	....	....	....
	rock fragment		1	0.2	–0.4	–0.4	....	–0.4	....	....	....	....
	feldspar			1	–0.3	–0.4	....	–0.4	....	....	....	....
	quartz				1	....	....	....	....	....	....	....
Texture	"a" size					1	–0.3	0.9	–0.4	....	....	....
	"a" sorting						1	–0.3	0.8	....	....	....
	"b" size							1	–0.3	....	....	....
	"b" sorting								1	....	....	....
	shape									1	....	0.2
	direction of orientation										1	....
	perfection of orientation											1

correlation matrix is resolved into the factor matrix which represents the correlations of the original variables with some smaller number of newly derived factors or components. These factors which are geometrically orthogonal to each other (thus statistically independent) span the "property" space and therefore constitute a system of bases vectors, in terms of which each variable is expressible as some linear combination.

Identification of these components (or factors) with conceptualized processes is enhanced by a rotational transformation which moves the factors (geometrically) to a position where each correlates with (or affects) the smallest possible number of properties. As mentioned earlier, we desire that each process influence a *few* of the properties significantly, rather than *all* of the properties insignificantly, in order to define the mutually exclusive sets described above.

The rotated factor matrix for this data appears in table 2. The first factor (F1) is most strongly loaded on the two estimates of grain size. In addition, proportion of matrix and perfection of grain orientation also show a positive association (though less strong) with this factor while the properties grain shape and proportions of feldspar and rock fragments correlate negatively with whatever underlying influence this factor represents. If it *is* some process, it is one which is most strongly expressed by variation in grain size; as the magnitude of the process increases the grain size becomes finer. Also the proportion of matrix material increases, and the degree of orientation increases. At the same time, the proportions of rock fragments and feldspar decrease, while the grains become more equidimensional in shape. The interaction between

TABLE 2

Diagonalized, simplified rotated matrix of factor loadings greater than 0.1

		Factors						
	Properties	F1	F2	F3	F4	F5	F6	F7
Texture	"b" size	0.9	−0.2	....	....	....	....	−0.2
	"a" size	0.9	−0.3	....	....	−0.2	....	....
	"b" sorting	....	0.9	....	....	....	....	....
	"a" sorting	....	0.9	....	....	....	....	....
	feldspar	−0.5	....	0.2	0.5	....	....	....
Composition	quartz	....	....	−0.9	....	....	....	....
	mica	....	....	....	−0.9	....	....	....
	rock fragment	−0.2	....	0.4	0.2	0.8	....	....
	matrix	0.3	....	0.4	0.2	−0.8	....	....
Texture	direction of orientation	....	....	....	....	....	0.9	....
	shape	−0.2	....	....	....	−0.2	−0.2	0.8
	perfection of orientation	0.2	−0.2	....	0.2	0.3	....	0.7
% Accounted for		18%	15%	12%	10%	12%	8%	10%
							Total	85%

the textural and compositional properties is particularly noticeable in the pattern that defines this factor.

The second factor (F2) is most strongly expressed by variation in size sorting of the quartz grains and less strongly by grain size and perfection of orientation. The underlying process reflected by the properties in this factor is one whose effects tend to increase the sorting of the material. Also as this influence increases in its magnitude, grain size and perfection of orientation tend to decrease. This factor expresses itself only in terms of textural properties.

The third factor is loaded only on compositional properties of which quartz proportion is the most dominant (negative association) with subsidiary positive loadings on matrix, rock fragments, and feldspar.

The fourth factor loads most highly on mica proportion (negative) with subsidiary lesser positive loadings on feldspar, rock fragments, matrix, and perfection of orientation.

The fifth factor represents some hypothetical influence which is correlated with the compositional variables; positively with proportion. The textural properties grain size and shape are negatively correlated with this factor indicating that its effects are also not wholly confined to the compositional variables.

Factor six is dominated by mean orientation direction while factor seven represents the effects of some process positively correlated with grain shape and perfection of orientation and negatively associated to a lesser degree with grain size (all textural properties). In other words, as the magnitude of this influence increases the grains become more elongate and more perfectly oriented.

DISCUSSION OF RESULTS

These results suggest the following:

First, if only four hypothetical influences (provenance, erosion-transportation, deposition, and diagenesis) constitute the major processes whose effects account for the variability in the measured properties, we would expect to have been able to explain a major portion of this variation in a four-dimensional space (four factors). In the present case, seven independent factors are required to account for 85 percent of this variation. This suggests the existence of closer to seven independent processes (definable by these properties) rather than the four originally proposed at the outset of this investigation. Griffiths (1966) has presented a seven component idealized model for associating factors with variation in measured properties of detrital sediments. It is thus evident that a four process model is overly simple in evaluating major effects of sedimentation processes.

Second, it appears that certain properties as operational measures of the underlying processes are perhaps redundant. For example, feldspar proportion is correlated with three different factors but dominates none of them. Therefore, this property reflects the effects of at least three of the processes to varying degrees, but none uniquely.

Third, with respect to the present analysis, the first factor appears to represent effects attributable to the general "competence of the transporting medium" due to its strong expression in grain size variation. The effects of the transportation processes on the observed composition of the rock are evidenced by the subsidiary loadings of this factor on a number of compositional variables, as shown in table 2.

The second factor, interpreted as representing "variation in the energy of the depositional environment" is reflected by its strong correlation with grain size sorting. The fact that grain shape is uncorrelated with this factor suggests that shape of the grains is non-influential in determining the degree of size homogeneity of the sediment.

The following three factors appear to represent components related to "source area", and the final two to the processes (presumably hydraulic) that determine the degree and direction of orientation of the individual grains.

These results suggest that the interpretation of effects of sedimentation processes from measurements of petrographic properties is complex since the patterns of variation displayed by the properties reflect interaction among the processes rather than unique ones.

It is also seen that the effects of hydraulic influences are most dominant and that variables measured on the rock properties carry little information related to the original source area of the material.

As additional analyses of this type become abundant, it is possible that certain unique factors of a similar nature will continually appear. If these can be given some objective meaning related to natural sedimentation processes, it should then become possible to make genetic comparisons of sedimentary rocks on the basis of these factors; it should also be possible to classify these rocks, in terms of genesis, into more meaningful groups than can be achieved by schemes based on variation in the raw properties.

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