Rohana, (1991) 3, 1 - 11

Use of Heavy Mineral Analysis in Determining Provenance of Coastal Sediments: A Case Study from Sri Lanka

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Introduction

Heavy minerals are resistant materials that survive chemical and mechanical weathering for considerable periods of time. They can serve therefore, determine the sources of sediments in depositional environments. Some researchers (Krumbein & Tukey, 1956; Carrol, 1957; Imbrie & Van Andel, 1964; Callahan, 1979) have used this technique in fluvial and denudational environments. The application of heavy mineral analysis in determining the provenance of sediments of coasts has received little attention.

Many coastal tracts of the world have been submerged by a Holocene marine transgression giving rise to embayments and irregular coasts. When the high sea level was regressed, diversified depositional forms, such as sand spits, bars, barriers, beach ridges, etc, were formed in front of the embayments and irregular coasts (Bird, 1978; Leont'yev, 1969; Weerakkody, 1987, 1988a; Verstappen, 1987). Large-scale sediment dynamics induced by the Holocene marine transgression and regression of these tracts, however, are not yet known completely due to lack of suitable techtiques. The objective of this study is therefore, to examine the use of heavy mineral analysis in determining the provenance of sediments in a depositional coast which has been developed in sequential stages since the Holocene marine transgression and regression.

The area and its geomorphological evolution

The coastal area investigated in this study is the Koholankala coastal system of the SE coast of Sri Lanka, which was submerged around 4000 years BP by the Holocene marine transgression (Verstappen, 1987). The geomorphology and the coastal development of the system have been analysed in detail by the author in three sequential studies (Weerakkody, 1985; 1986; 1988a). Accordingly, landforms of the Koholankala coastal zone consist of plantation surfaces and denudational valleys carved in rocks of Precambrian and Palaeozoic ages. They slope towards active lagoons and river beds (Fig 1 d). The major marine landforms are the huge barrier chains crowned by longitudinal dunes in three generations (Weerakkody 1990).

Many fossiliferous coastal landforms such as sand spits, bay-head barriers, bay beaches and sea beaches formed as a result of the Holocene marine transgression and regression are observed in the hinterland. They exhibit sequential growth of the coast which has been developed into four development stages (Weerakkody, 1985, pp78-81, 1988).

The first stage has been characterized by a funnel-shaped embayment or the 'former bay of Koholankala' formed by the mid-Holocene submergence. The high sea level has risen to the foot of the planation surfaces and to the lower parts of the valleys (Fig 1 a). When the high sea level receded, two bay-head barriers (hereafter referred to as fossilized barriers) marking the second stage have been formed converting the funnel into a moderately deep embayment. The barriers, obviously formed in a low energy environment, are characterized by a high content of silt and clay. At the same time, an incipient spit had also formed in the bay under low-energy conditions. It subsequently developed into a huge spit in the early embayment, separating into two segments (Fig b & c). The western headland protected the system from high energy impact. During the third stage the two headlands became connected by a long barrier chain (hereafter referred to as subrecent barriers). The fourth stage is characterized by dunes (DL1, DL2 and DL3) developed on the subrecent barriers and by the present wide sandy beaches. Figure 1 d shows these stages.

According to the evolutionary stages, landforms such as planation surfaces, valleys, natural levees, etc, of stage 1 must have supplied materials to the landforms such as the sand spit, fossiliferous barriers, former sea beaches, lagoonal beaches, lagoonal floors, etc, of stage 2. However, the subrecent barriers must have been formed under a large amount of sediment load supplied by the landforms of stage 1 and 2, and/or by outer sources. Such subrecent barriers dominate the SE and NE coasts of Sri Lanka (Preu & Weerakkody, 1987, Weerakkody, 1988 b)

Examination of the provenance of sediments would help to answer two important questions;

a) Have sediments been supplied by the landforms in the first stage to the landforms of the second stage when the high sea level receded?

b) Have sediments been supplied to the landforms of third and fourth stages by the landforms of first and second stages or by outer source/s due to the recession of the high sea level?

Method and techniques

To answer these two questions, provenance of sediments was studied comparing similarity and dissimilarity of the distribution of heavy minerals pertaining to the landforms of each stage.

Twenty-two samples, collected representing every landform of each stage, were analysed in the NUFFIC laboratory of the Department of Geography, University of Colombo. After having processed and sieved, the grains were separated into fractions. A heavy mineral separation in bromoform was carried out on the 0.088—0.125 mm fraction, derived from the representative samples. The heavies were mounted on slides using Canada balsam. The heavy minerals were identified by means of a polarizing petrographic microscope and counted according to the linear counting method.

The heavy mineral identified and counted for each sample consist of biotite, hornblende, hypersthene, garnet, monazite, rutile, opeque and zircon. The amount of each heavy mineral of a sample is represented as a percentage of its total count. The provenance of sediments of the above mentioned landforms of the four stages can be tested using the distribution of heavy minerals along with the following hypotheses;

a) If the heavy mineral groups form the landforms such as planatation surfaces, former headlands, natural levee of the hinterland (or stage 1) resemble those from the landforms such as the fossilized spit, fossilized barriers, former beaches, lagoonal beaches, lagoonal floors of the second stage, it can be concluded that the hinterland did indeed supply the sediments of the landforms of stage 2. b) If the heavy mineral groups in the samples from the subrecent barrier chains, present beaches and sand dunes which represent stages 3 and 4 do not resemble those of stages 1 and 2, the materials of these forms were derived from other source/s.

To test these hypotheses, the data of heavy mineral counts were statistically treated to find the phenetic relationship between corresponding samples. One of the most reliable statistical methods used to find such phenetic relationships is the Weighted Pair Group Method -WPGA- (Sokal & Sneath, 1963). Accordingly, the method helps to calculate the Normalized Euclidean Distance (djk) which supports to examine the relationships of the corresponding samples by means of graphical representation. The Normalized Euclidean Distance (djk) is derived using formula;

$$djk = \frac{\left(\sum_{i=1}^{n} X^2_{ij} \quad \sum_{i=1}^{n} X^2_{ik} - 2 \sum_{i=1}^{n} X_{ij} \, X_{ik}\right)^{1/2}}{n}$$

where i — group of minerals;
jk — samples.

The length of the Euclidean Distances can be used to find the phenatic relationships between the corresponding samples, if the above mentioned hypotheses are written again as follows;

a)	(planation surfaces,)		(fossilized spit,)
	(former headlands)	should be	(fossilized barriers)
	(natural levee of)	closed to	(former beaches)
	(stage 1)	and clustered	(lagoonal floors of)
		with	(stage 2)

b)	(planation surfaces)		
	(former headland,)		
	(natural levee)		
	(of stage 1 and)	should be	(recent barriers)
	(fossilized spit,)	situated	(recent dunes)
	(fossilized barriers)	further from	(and subrecent barriers)
	(former beaches)		(of stage 3 and 4)
	(lagoonal beaches)		
	(lagoonal floors)		
	(of stage 2)		

Statistically treated data were drawn into a dendrogram and into twenty-two histograms in order to test these hypotheses.

Results and conclusions

The computed Normalized Euclidean Distances drawn into dendrogram are shown in Fig 2. A visual assessment of phenatic relationships of the corresponding samples can be obtained with the help of the dendogram. The landforms such as planation surface (no. 1) and former headland (no. 6) of stage 1 are closely related to landforms such as fossilized spit (no. 7), lagoonal beach (no 19) of stage 2. Again the planation surfaces (nos. 2 and 3) of stage 1 are related to former beach (no. 12) of stage 2 and to recent headland (no. 17). Natural levee (no. 5) of stage 1 and lagoonal beach (no. 20) of stage 2 are also closely associated. These close associations support the hypotheses that the materials of landforms pertaining to stage 2 have been derived from the landforms of stage 1 or from the hinterland. The recent dunes (no. 14, 15, 13 and 16) and recent beaches (nos. 10 and 17) of stage 4 show long Normalized Euclidean Distances when compared with those of the landforms of stages 1 and 2. In addition, close relationships between the landforms such as fossilized spit (no. 7), lagoonal beaches (nos. 19 and 29), lagoonal floor (no 22) and fossilized barrier (no 8) and former beach (no. 11) of stage 2 show that they have been formed by materials received from homogeneous source/s. The landforms such as recent beaches (nos. 17 and 10), recent dunes (nos. 14, 15 and 13), recent headland (no. 4) and subrecent barrier (no. 8) of stages 3 and 4 are situated further from the landforms such as planation surfaces (nos. 1 and 3) former headland (no. 6), fossilized spit (no. 7), lagoonal beaches (nos. 19 and 20), former beach (no. 12), natural levee (no. 5) and lagoonal floor (no. 22) of stages 1 and 2 indicating that the landforms of stages 3 and 4 have not been receiving materials from the landforms of stages 1 and 2. These dissimilarities suggest that the second hypothesis is also correct.

These conclusions can be further substantiated by the rearrangement of the histograms according to the clusters appeared in the dendrogram of Fig 2. The results given by the computer are shown in Fig 3 a, b and c. Comparison of samples in each cluster of samples shows that the distribution of eight heavy minerals within a cluster (a or b or c) is similar to each other with only slight differences. The cluster 1 of Fig 2 consists of landforms such as planation surface (no 1), former headland (no 6), fossilized spit (no. 7), lagoonal beach (no. 19), recent dune (no. 14) and recent beach (no 10) which belong to both stage 1 and 2 so indicating that the first six samples are very similar in their distribution of heavy minerals (Fig. 3 a) because the landforms of stage 1 have supplied materials to form the landforms of stage 2 as assumed in hypothesis 1. Even though the recent dune (no. 14) and recent beach (no. 10) are clustered together, they are situated with greater Normalized Euclidean Distances (Fig. 2) or in the lower parts of the cluster (Fig. 3 a) because of the dissimilarity of material distribution. Cluster 2 consists of the landforms of stages 1 and 2 (Fig. 2) exhibiting the same relationship (Fig. 3 b) and it can be used to substantiate the hypothesis 1. Even though the recent beach (no. 17) and recent headland (no. 4) are clustered together, they are situated with greater Normalized Euclidean Distances or in the lower part as demonstrated by Fig 2 and Fig 3 b respectively, because the materials of the landforms of both stages have not received from similar source/s. The clusters 3 and 4 appearing together in Fig. 3 c also shows similar pattern with the differentiation between the fossilized barrier (no. 2), former beach (no. 11) subrecent barrier (no. 18) and recent dunes (nos. 15 and 13). Sample nos 16 and 21, however, cannot be used for the above mentioned conclusions.

The summarized data in Fig. 2 helps to deduce that the landforms of stages 3 and 4 are not closely associated with the landforms of stages 1 and 2. A similar conclusion can be substantiated from Fig. 3 a, b and c in which all landforms of stages 3 and 4 are situated in the lower parts of the clusters of histograms. Accordingly, the hypothesis 2 seems acceptable. This means that the materials of landforms pertaining to stages 3 and 4 have not received their sediments from the landforms of stages 1 and 2, but from outer source/s.

It can be assumed that when the high sea level being gradually receded during late-Holocene time, the landforms of stages 3 and 4, especially the barrier chains have developed along the SE coast of Sri Lanka receiving large amount of sediments from the continental shelf. Further research on similarity and dissimilarity of heavy mineral distribution among the continental shelf and the barrier chains would help to assess this assumption.

Acknowledgements

I wish to express my deep gratitude to Prof M. A. Pemadasa, University of Ruhuna, who read and gave valuable comments on the manuscript, to Dr Miss K. Gunawardana, who gave the permission to use the NUFFIC sedimentological Lab of the University of Colombo, and to Mr. M. Liyanage who helped me with laboratory work.

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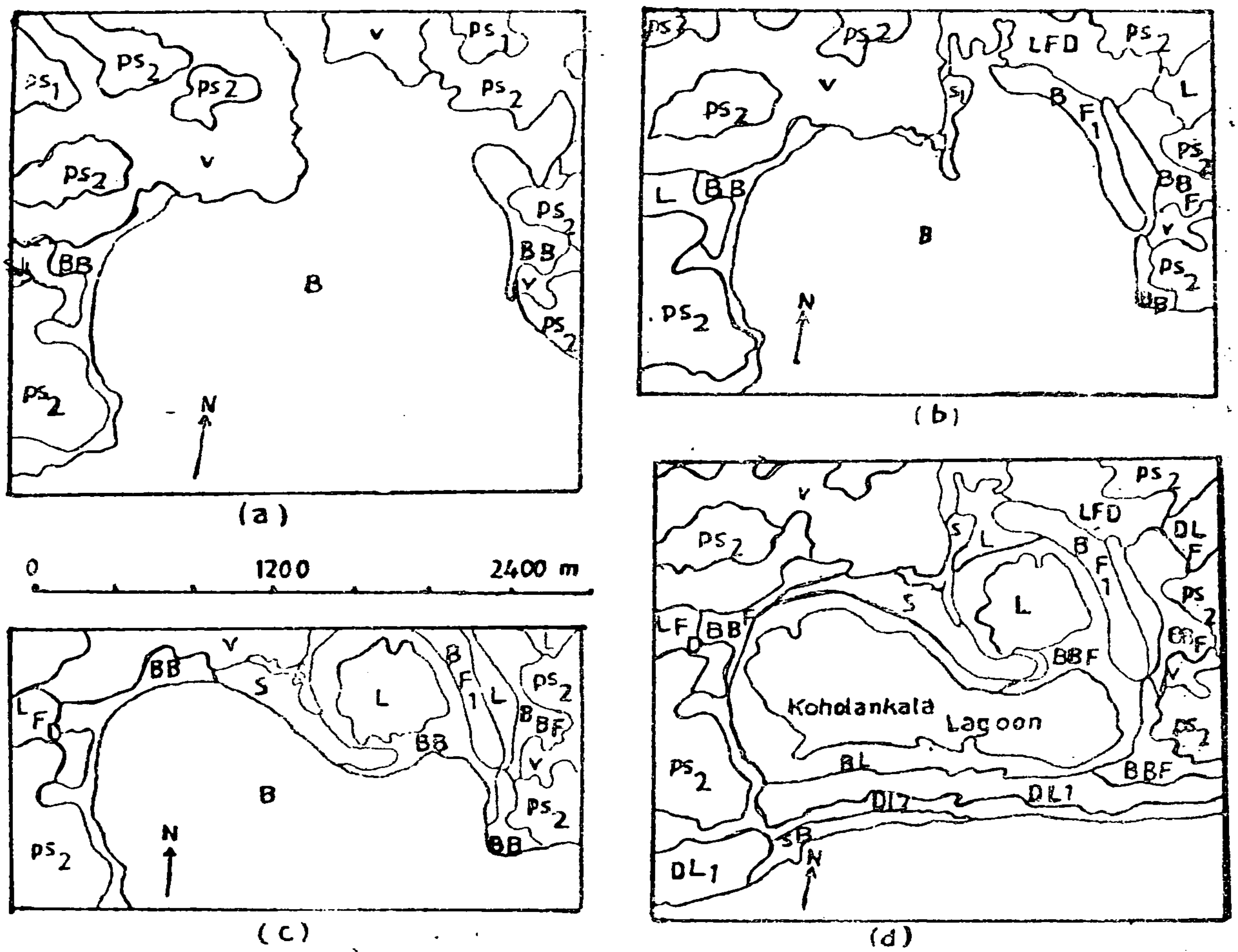


Figure 1 The effect of sea level changes on the development of the Koholankala lagoon in four stages since Mid-Holocene, (a) The planation surfaces (PS1, PS2) and valleys (V) were submerged by the marine transgression to form a funnel shaped embayment (B) and baf beaches (BB), (b) When the sea level dropped, a mid-bay bar (BF1) and an incipient spit (S1) were formed in front of the neck of the funnel. Subsequently lagoons (L) were dried out forming dried out lagoonal floors (DLF). (c) Due to the gradual dropping of the sea level, the incipient spit grew larger (S). (d) The oval shaped bay formed during the third stage (c). ultimately was cut off from the sea by a chain of barriers crowned by sand dune (DL1. DL2). The Koholankala lagoon is now characterized by wide lagoonal beaches (BL).

NORMALIZED EUCLIDEAN DISTANCES

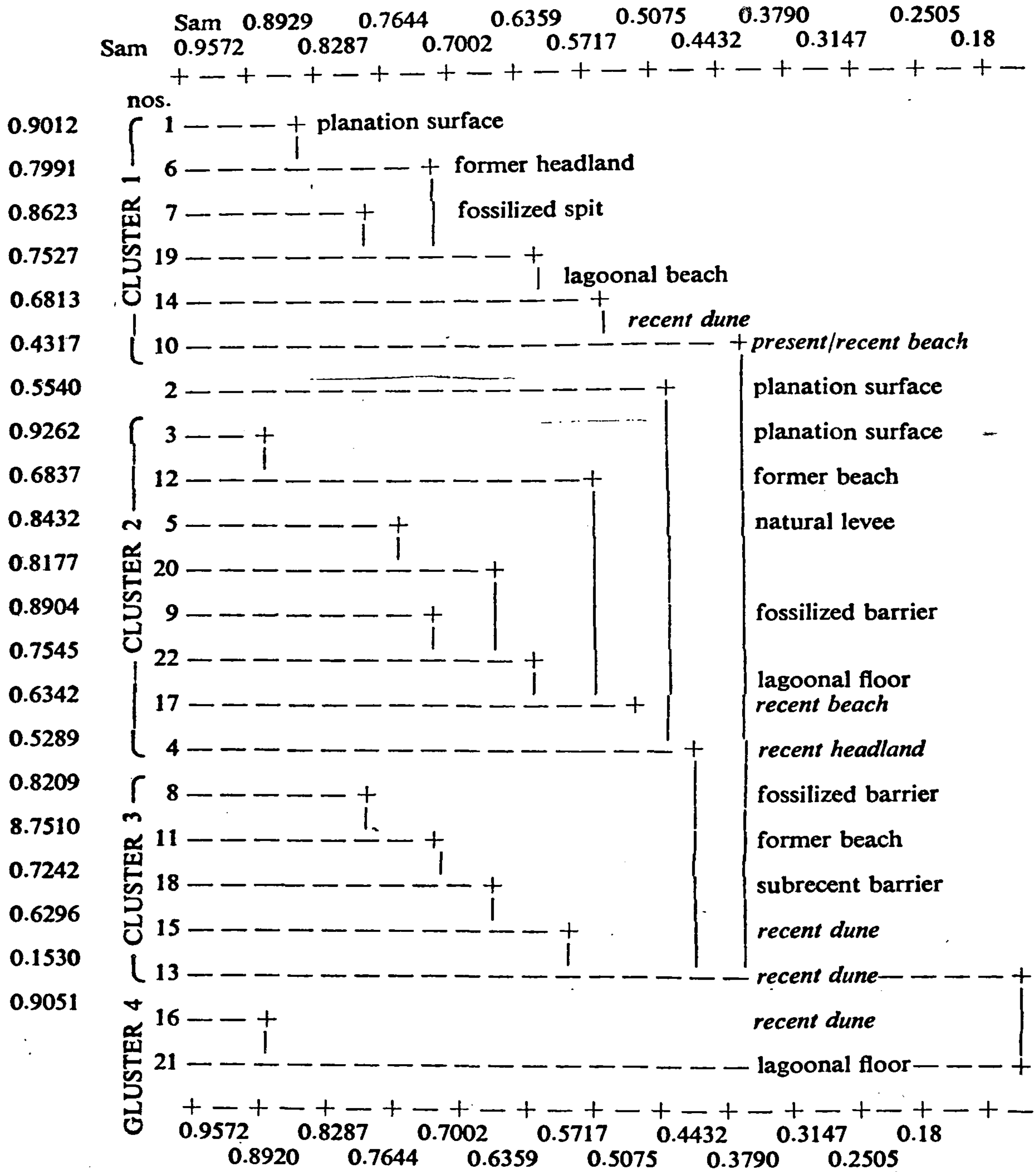
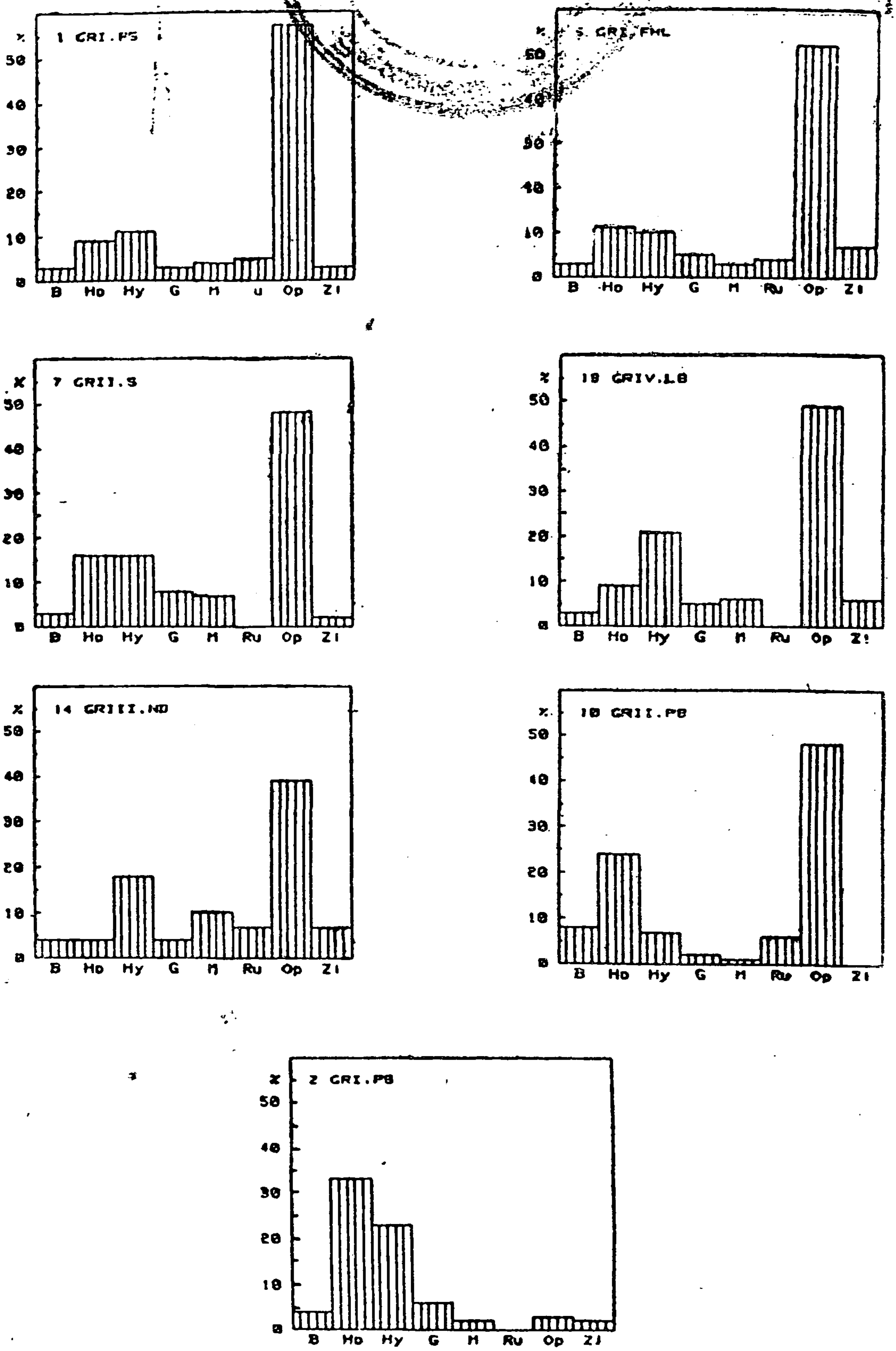
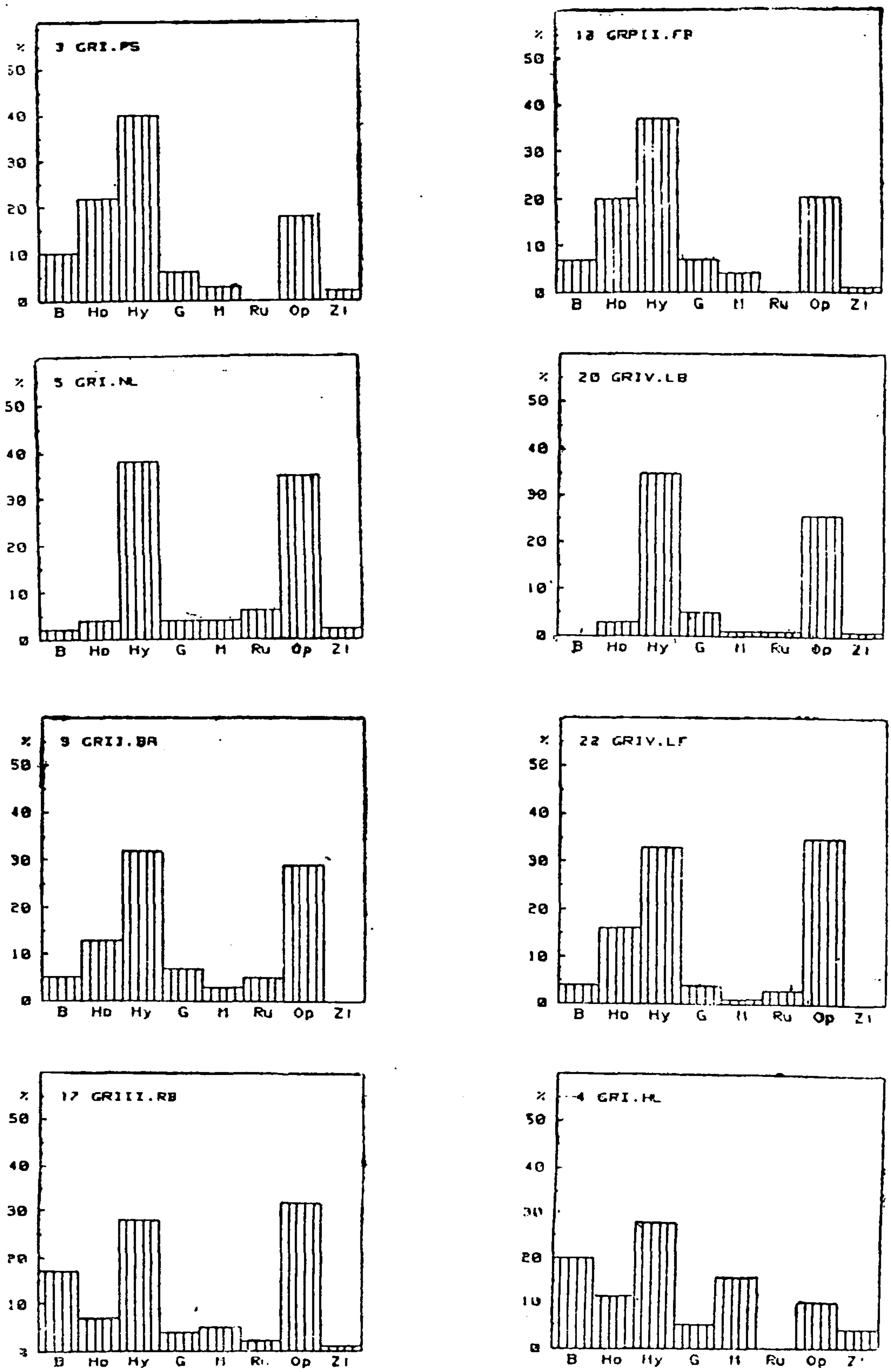


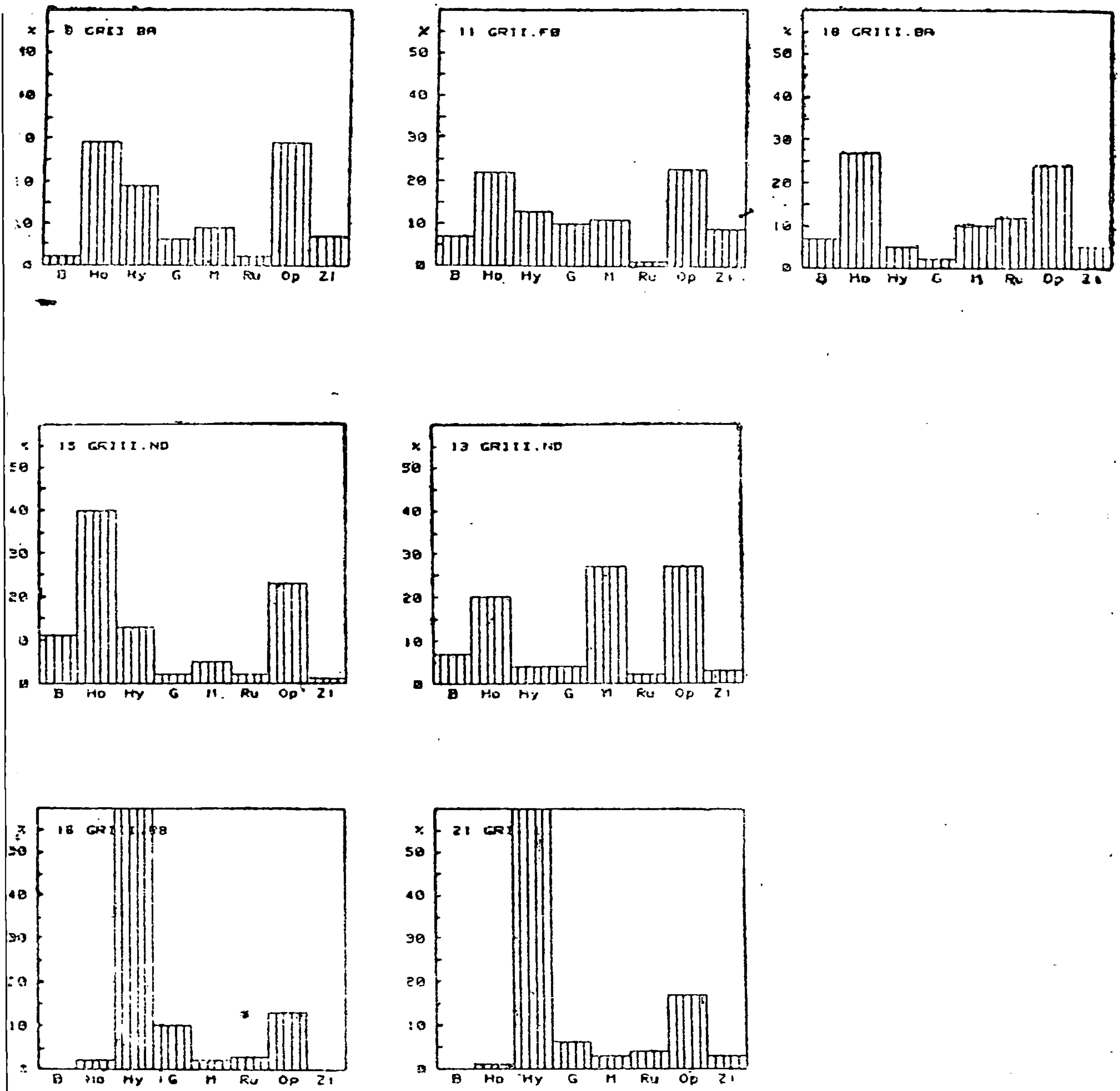
Figure 2 Dendrogram showing the clustering of the samples. The greater the difference between the Normalized Euclidean Distances, the lesser is the phenatic relationship between the corresponding samples. The formations of the recent stages are underlined. Compare with Fig 3 a, b and c.


1 GRI.PS
5 GRI.FHL
7 GRII.S
19 GRIV.LB
14 GRIII.ND
18 GRII.PB
2 GRI.PB
%
0
10
20
30
40
50
B
Ho
Hy
G
M
Ru
Op
Zi

(a)


3 GRI.PS
18 GRPII.FP
5 GRI.NL
20 GRIV.LB
9 GRII.BA
22 GRIV.LF
17 GRIII.RB
4 GRI.HL
%
50
40
30
20
10
0
B Ho Hy G M Ru Op Zi

(b)



(c)

Figure 3 a, b and c—The heavy mineral distribution. B—Biotite; HD-Hornblende; Hy-Hypersthene; G-Garnet; M-Monc site; Ru-R7tile; OP-Opeq'e; Zi-Zircon. Note the similarity within a cluster and dissimilarity among clusters of a, b and c. Last two samples appeared in the lower portion of Fig. 2 have been included into cluster c, even though they formed into cluster 4 in the dendrogram.