Bulletin de la Société belge de Géologie Bulletin van de Belgische Vereniging voor Geologie	100/1-2	pp 203-218	Bruxelles Brussel

STUDY OF THE RELATIONSHIPS BETWEEN THE PHYSICO-CHEMICAL, MINERALOGICAL AND FIELD VARIABLES OF BELGIAN CLAYS AND LOESS-LOAMS BY MEANS OF PRINCIPAL FACTOR, CLUSTER AND CANALS ANALYSIS

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ABSTRACT

26 Belgian clays and loess/loams from cretaceous until recent age have been characterized mineralogically, chemically and physically. From 56 originally considered variables 19 have been selected on the basis of their correlation coefficients to perform a factor, a cluster and a canals analysis. As "field" variables the geological formation, the sedimentation type and exploitation area have been taken into consideration. The canals analysis allowed to represent in a two dimensional diagram the loess/loam, the alluvial, the coastal and the marine samples as distinct groups based on physico-chemical and mineralogical data. Na_2O, Al_2O_3, total Fe_2O_3, Pfefferkorn plasticity index, smectite, pyrite and organic matter prove to be most useful parameters.

KEY WORDS

Clays, clay mineralogy, sedimentology, geostatistics.

1. INTRODUCTION

The aim of this study is to get a better insight in the way in which field observations are codeterminative in structuring the information derived from the study of physico-chemical and mineralogical variables of a set of clays and silts.

26 clays and loess/loams from important Belgian clay deposits, most of which are still exploited, have been analyzed chemically, physically and mineralogically (Ottenburgs *et al.*, 1983).

The sample locations are shown on map 1. The ages of these clay and loess/loam deposits range from Cretaceous to Quaternary (table 1). They can be divided into four groups based on their sedimentary environment :

I. Marine environment : Rupelian clays from Sint Niklaas (15, 16), from Kruibeke (17) and from Wijer (18) ; Bartonian clay from Assenede (20) ; Paniselian clays from Egem (21, 22) and Ypresian clays from Kortemark (23, 24).
II. Coastal environment : Holocene tidal flat clays from Hoeke (5) and Oudenburg (6), Pleistocene clay from Henis (19),

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Cretaceous clays from Welkenraedt (25, 26).
III. Alluvial environment : Meuse clay (1) and Scheldt clays (2, 3, 4).
IV. Loess and loam deposits : Weichselian silts from Denderwindeke (7, 8), from Tienen (9), from Dikkele (10) and from Burst (11, 12).

From the 56 original chemical, physical and mineralogical variables 19 have been finally selected (on the basis of the correlation matrix) to perform a factor, a cluster and a canonical analysis (CANALS).

The objects are represented as dots in two dimensional scatter diagrams. The coordinate axes of the diagrams correspond to mathematically created variables (Symons & Wauters-Vuylsteke, 1985). Several sets of such mathematically created variables are presented. Each of these set illustrates in an optimal way, by means of a minimum of new variables, a definite aspect of the data structure.

Special attention is paid to :

a. the recognition of the contribution of the original variables ;
b. the demonstration of well defined groups of objects ;
c. an explanation for the position of the objects based on external information.

The set of normalized principal components is considered as a factor set. The factors of a factor set always are uncorrelated ; they are normalized on zero average and unit sum of squares.

A scatter diagram with e.g. the first and second factor represents the projections of the points from a swarm of normalized principal components to these factors.

If there exists a second set of variables - in this case the field variables - the factorization of the variables of the first set can be carried out in such a way that the scatter diagram(s) can be interpreted optimally in function of the information given by the second set. The highest ranking factor of the first set of variables is the one which sum of squares of the correlations with the principal components of the second set of variables is maximal. The

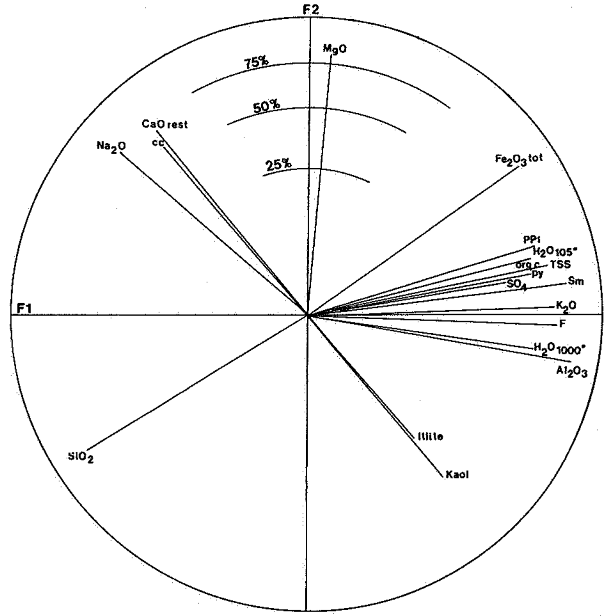


Figure 1 : Principal factor analysis : loadings on F1*F2 plot.

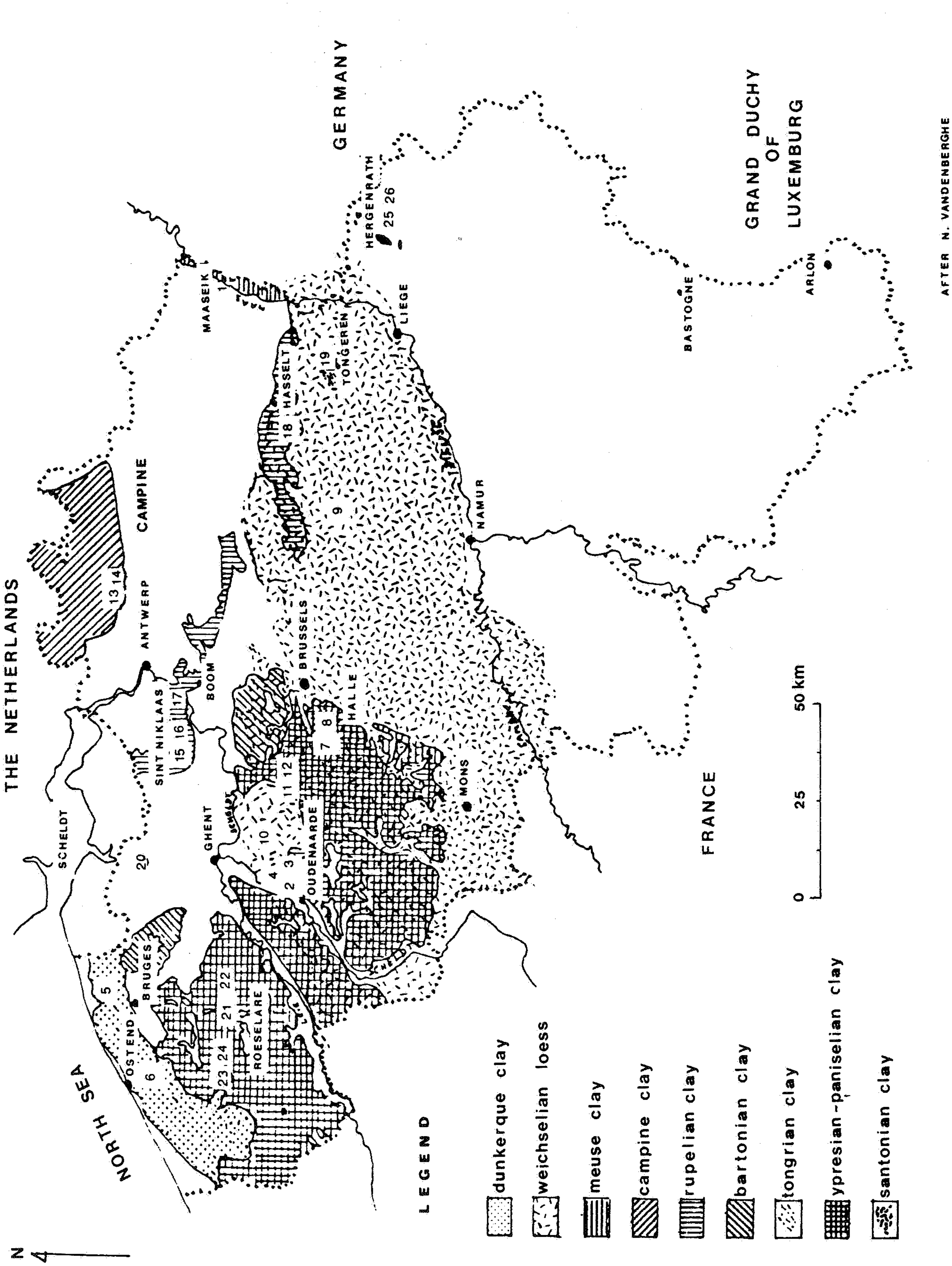
second factor explains the second highest part of the total variability, and so on. These factors are called the canonical variables of the first set.

A plot of the first against the second canonical variable shows the structure of the first data set in the best interpretable way with regard to the data of the second set. The method is based on the calculation of the correlation coefficients in the classical way.

In order to characterize the information from the field, four systems have been selected :

1. rough stratigraphical position ;
2. finer specification of the stratigraphical position (upper, lower ...) ;
3. sedimentary environment ;
4. area of exploitation.

For each of these category systems a set of exclusive circumstances is considered. It is important to notice that it is impossible to attach *a priori* a numerical value nor to these circumstances neither to the objects characterized by these circumstances. Similar category systems are called nominal variables, and the characteristic situations the typical classes of these nominal variables. If one succeeds in attaching *a posteriori* a numerical class value to the nominal classes, the nominal classes can be regarded as regular numerical variables. In that capacity they can be analysed.



Map 1 : Distribution of the Belgian clay and loess deposits, and location of the samples.

Table 1 : Schematic representation of stratigraphical, sedimentological and location data concerning the Belgian clay and loess deposits.

Stratigraphic Formation	Exploitation Area	Sedimentary Environment	Codenumber clay/silt	Literature
Holocene alluvium of the Meuse	*Meuse plain, Limburg*	*Fillings of abandoned river-beds; flood plain sediments*	*1*	*Paulissen*
Holocene alluvium of the Scheldt	*Oudenaarde, Ghent*	*Flood plain sediments in the Scheldt alluvial plain*	*2, 3, 4*	*Tavernier (1948)*
Holocene Dunkerque clays	*Polders, coastal plain*	*Tidal flat sediments*	*5, 6*	*Baeteman; Tavernier (1970)*
Upper and middel Weichselian loam and loess	*Middle Belgium*	*Windblow silts from the northern glacial regions*	*7, 8, 9, 10, 11, 12*	*Tavernier (1948)*
Lower Pleistocene Campine clay	*Campine, Antwerp*	*Tidal flat sediments*	*13, 14*	*Paepe; Zagwijn; Dricot; Van Daele*
Rupelian Boom Clay	*Mechelen, Boom, Sint Niklaas, South Limburg*	*Marine shelf deposits*	*15, 16, 17*	*Vandenberghe; Decleer*
Weathered Boom Clay	*Waasland, Hasselt*	*Meteoric weathering of marine clay*	*18*	*Janssen et al.,*
Lower Olicogene Henis clay	*Tongeren, Boutersem, Tienen*	*Lagoon or brackish lake*	*19*	*Gilbert et al.,*
Bartonian Asse clay	*NW of Brussels, Asse, E of Bruges(Oedelem)*	*Marine shelf clay*	*20*	*Calembert (1947)*
Kortemark Silt (Plc of geological map)	*Southern Flanders*	*Marine shelf clay*	*21,22*	*Linster; Van Oyen; Steurbaut & Nolf*
Aalbeke clay (Plm of geological map)	*Courtray*	*Shallow marine or lagoonal clay*		*De Moor & Geets*
Ypresian clay	*Southern Flanders, Southern Hainault, Southern Brabant*	*Marine shelf clay*	*23, 24*	*Gulinck (1967) Notebaert*
Upper Landenian clays	*NE Hainault, SE Hesbaye*	*Fluvio-lagoonal clay*		*Gulinck (1973)*
Aachen Formation, Santonian Hergenrath clay	*Welkenraedt*	*Lagoonal clay*	*25, 26*	*Calembert*

Variable	C	Factor 1	Factor 2	Factor 3	Factor 4
SiO2	a	-0.73663	-0.47494	-0.39331	-0.18947
Al2O3	b	0.90796	-0.16511	0.18482	0.16444
Fe2O3 tot.	c	0.72267	0.52159	-0.24848	-0.12901
MgO	d	0.07105	0.90365	0.19281	0.03282
Na2O	e	-0.63820	0.56716	0.22900	0.12023
K2O	f	0.84641	0.03054	0.04325	-0.12287
CaO rest	g	-0.52035	0.64577	0.25637	0.17205
H2O 105°	h	0.75608	0.19377	-0.46808	0.17316
H20 1000°	i	0.77061	-0.12386	0.38728	0.00102
So4--	j	0.66520	0.11256	0.01594	-0.38198
Org. C	k	0.74634	0.15884	0.25370	-0.46472
F	l	0.84907	-0.03689	0.21023	0.19563
PPI	m	0.77440	0.24144	-0.45879	0.25226
TSS	n	0.80453	0.16348	-0.29751	0.25073
Calcite (cc)	o	-0.48912	0.58623	0.27772	0.24951
Pyrite (py)	p	0.76704	0.14672	0.28903	-0.45050
Smectite (sm)	q	0.87969	0.11154	-0.23306	0.20838
Illite (ill)	r	0.36100	-0.42947	0.34412	0.42974
Kaolinite (kaol)	s	0.47039	-0.57292	0.46317	0.22847

VARIANCE EXPLAINED BY EACH FACTOR			
Factor 1 9.374698	Factor 2 3.148559	Factor 3 1.732636	Factor 4 1.241937

FINAL COMMUNALITY ESTIMATES				
SiO2 0.958785	Al2O3 0.912847	Fe2O3 tot 0.872687	MgO 0.859879	Na2O 0.795859
K2O 0.734313	CaO rest 0.783108	H2O 105 0.858288	H2O 1000 0.759165	SO4 0.601322
Org. C 0.862578	F 0.804754	PPI 0.932109	TSS 0.825373	CC 0.722284
PY 0.896372	SM 0.884029	ILL 0.617857	KAOL 0.816221	

Table 2 : Principal factor analysis : loadings, variance and final communality estimates. (C = code).

To characterize the classes in a numerical way, the problem of finding solution(s) for a classical canonical correlation analysis will be reduced to the formulation of an eigen value problem, and can be approached by minimizing a well defined loss function. A loss function can be minimized over the class values for the nominal variables as well as over the weight to be awarded to the variables themselves (Gifi, 1981).

This strategy has been followed here to study a set of numerical physico-chemical, mineralogical values of clay samples on the one hand, and a set of nominal field variables of those materials on the other.

2. STATISTICAL TREATMENT OF DATA

2.1. Factor analysis

The results of the factor analysis are represented in tables 2 and 3, and figures 1 to 3.

Figure 1 (F1*F2) shows a group of variables with smectite, H_2O 105°C, total specific surface (TSS), Pfefferkorn plasticity index (PPI) determined as %wt adsorbed H_2O at 12.5 mm residual depth, organic carbon, pyrite and in

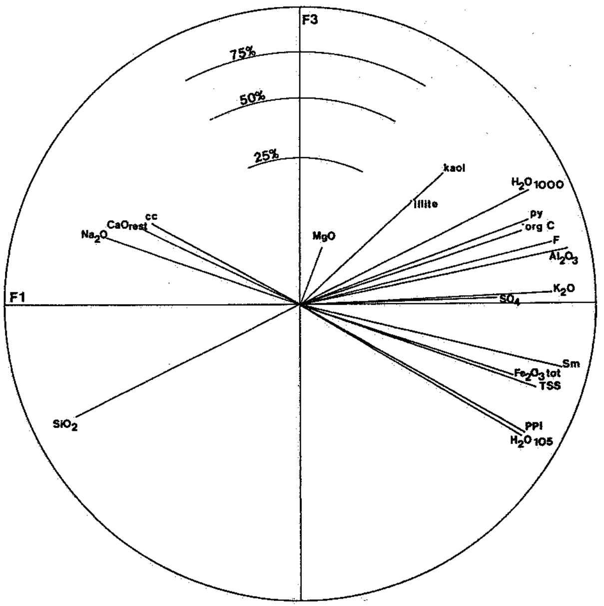


Figure 2 : Principal factor analysis : loadings on F3*F1 plot.

water soluble sulfates near factor 1, that can be considered as the smectite factor.

Illite and kaolinite are more or less isolated from this group due to the difference in MgO which has a high loading on factor 2. Al_2O_3, fluor, H_2O 1000°C and K_2O take an intermediate position between the clay minerals, while Na_2O, CaO rest (total CaO-CaO of calcite) and calcite lay at the opposite side.

Figure 2 (F1*F3) demonstrates a close relationship between smectite and total Fe_2O_3,

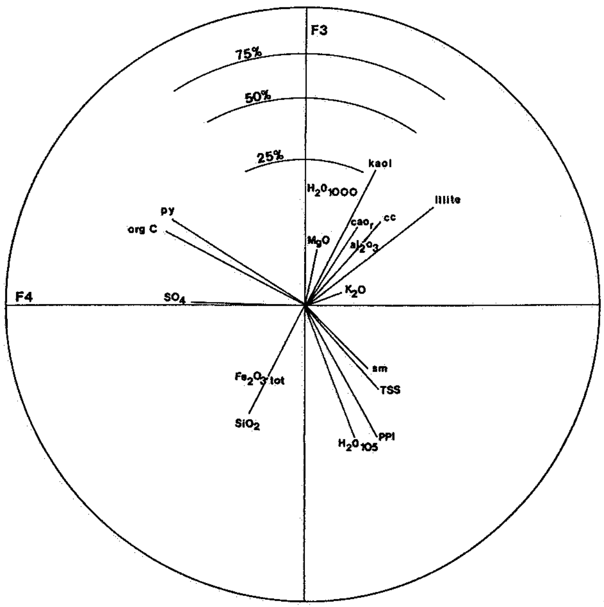


Figure 3 : Principal factor analysis : loadings on F4*F3 plot.

Na_2O, CaO rest and calcite are grouped at the opposite side. This means that the smectite in these clays is relatively rich in iron and rather poor in sodium and calcium. The good correlation between organic matter and sulfides (mainly pyrite) can be explained by the fact that both need reducing conditions from early burial depth onwards. The content of water soluble sulfates is determined by the degree of oxidation of the sulfides and by the amount of sulfides originally present.

Figure 3 (F3*F4) shows total Fe_2O_3 intermediate between smectite and pyrite. In this figure illite and kaolinite are separated from smectite because of the difference in H_2O 105°C and H_2O 1000°C. Factor 3 can be considered as the "water" factor.

2.2. Cluster analysis

A cluster analysis resulted in the following clusters of clays :

Cluster A : loess samples 7, 8, 9 and 11 ; river clays 2, 3 and 4 ; tidal flat clays 5 and 6.
Cluster B : coastal clays 19 and 25.
Cluster C : marine clays 17 and 20 ; coastal clay 13.
Cluster D : marine clays 22 and 23.
Cluster E : marine clay 16, river clay 1 and loam 12.
Cluster F : marine clay 18, coastal clays 14 and 26.
Cluster G : marine clays 15, 21 and 24 ; loam 10.

The heavy clays (rich in < 2 µm fraction) are spread over the clusters B, C and D. Figure 4 (F3*F4) shows that these clusters are clearly spearated from a central group consisting of clusters A, E, F and G. Cluster D is characterized by its considerable smectite, H_2O 105°C, PPI and TSS figures on the one hand, and by its low content of pyrite and organic matter on the other hand. Cluster B includes heavy clays with an important amount of illite and kaolinite, but poor in pyrite and organic matter. Cluster C groups heavy clays rich in pyrite and organic carbon, and moderately rich in smectite and illite. In figure 5 (F1*F2) the group consisting of the clusters A, E, F and G falls apart.

Concerning the position of the samples with regard to the variables (figure 6), the following statements can be made :

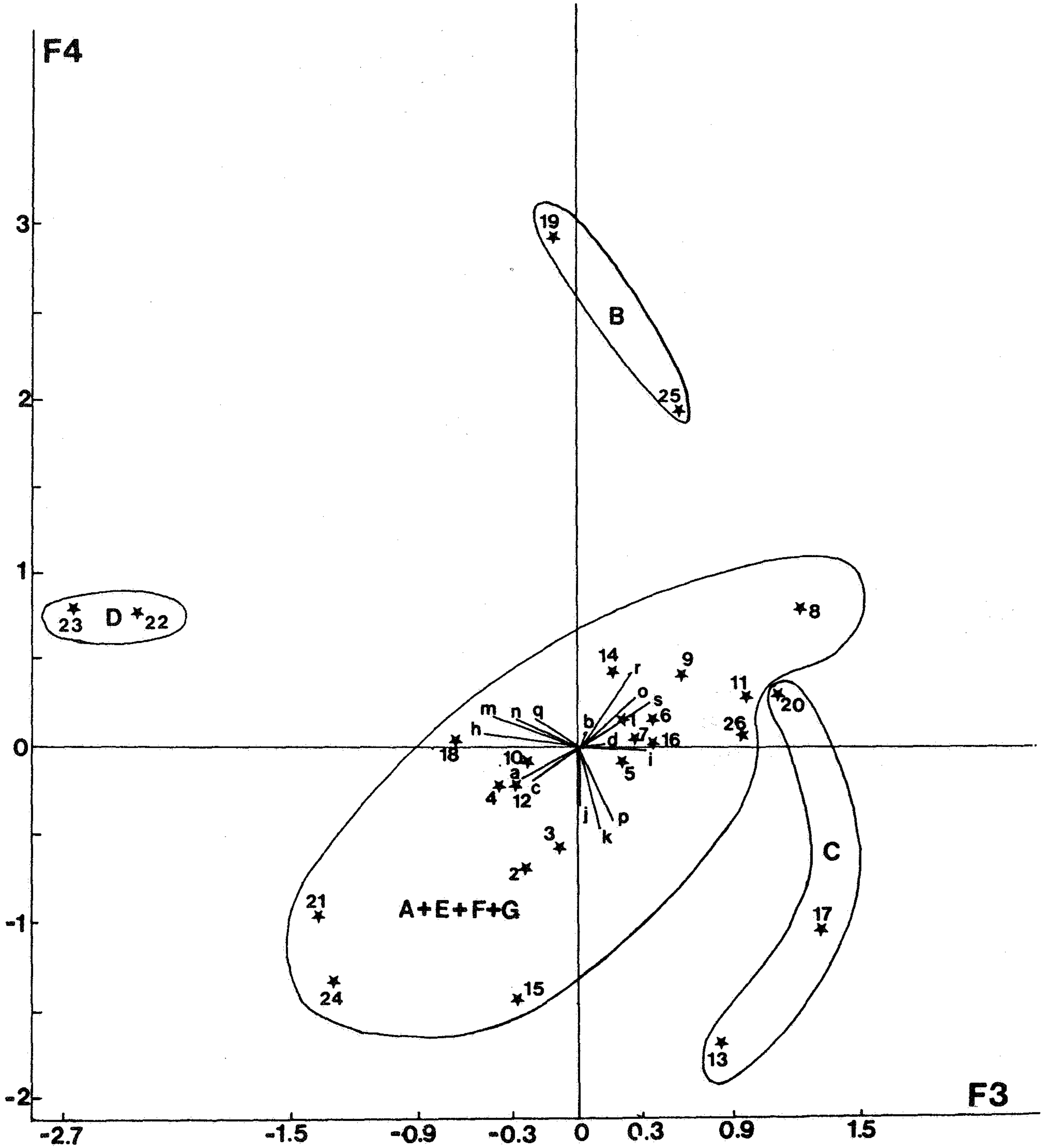


Figure 4 : Cluster analysis : loadings and scores on F4*F3 plot.

- the loess, Scheldt and tidal flat samples, as well as the samples rich in organic matter (> 0.9 %), mark relatively high at MgO (> 1.0 %) (cluster A) ;

- the samples rich in organic matter (cluster C) are also characterized by a high amount of total Fe_2O_3(> 4.5 %), total Fe_2O_3 includes the iron combined with sulphur in pyrite

- the loess, Scheldt and tidal flat samples (Cluster A) score low at total Fe_2O_3(< 4.5 %) but high at CaO (> 1.0 %)

- the loess, loam and Scheldt samples hold low amounts of smectite (< 12 % Sm), the Meuse and the rather sandy coastal and marine samples intermediate (14-20 % Sm), the heavy coastal and marine clays high to very high percentages (29-48 % Sm).

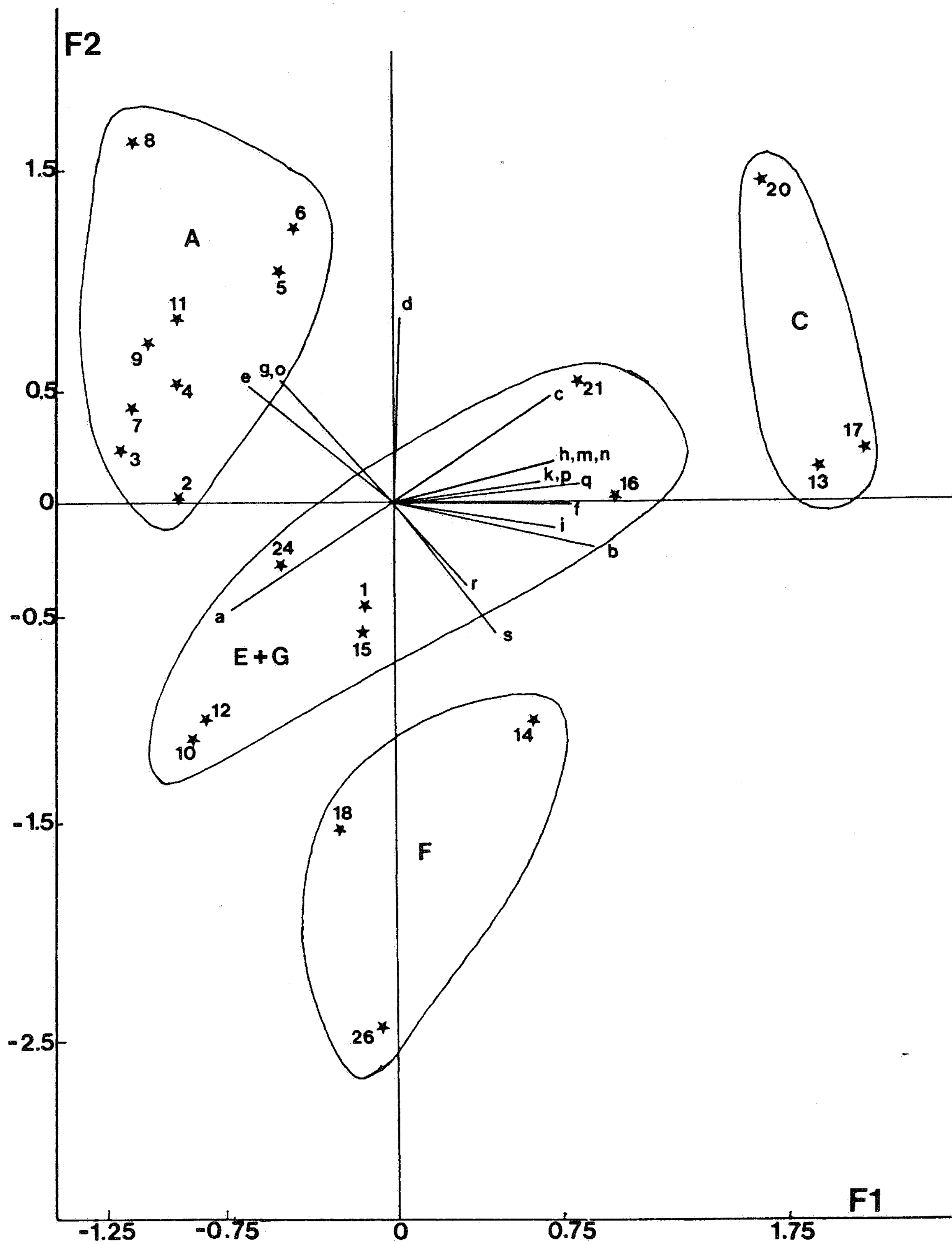


Figure 5 : Cluster analysis : loadings and scores on F2*F1 plot.

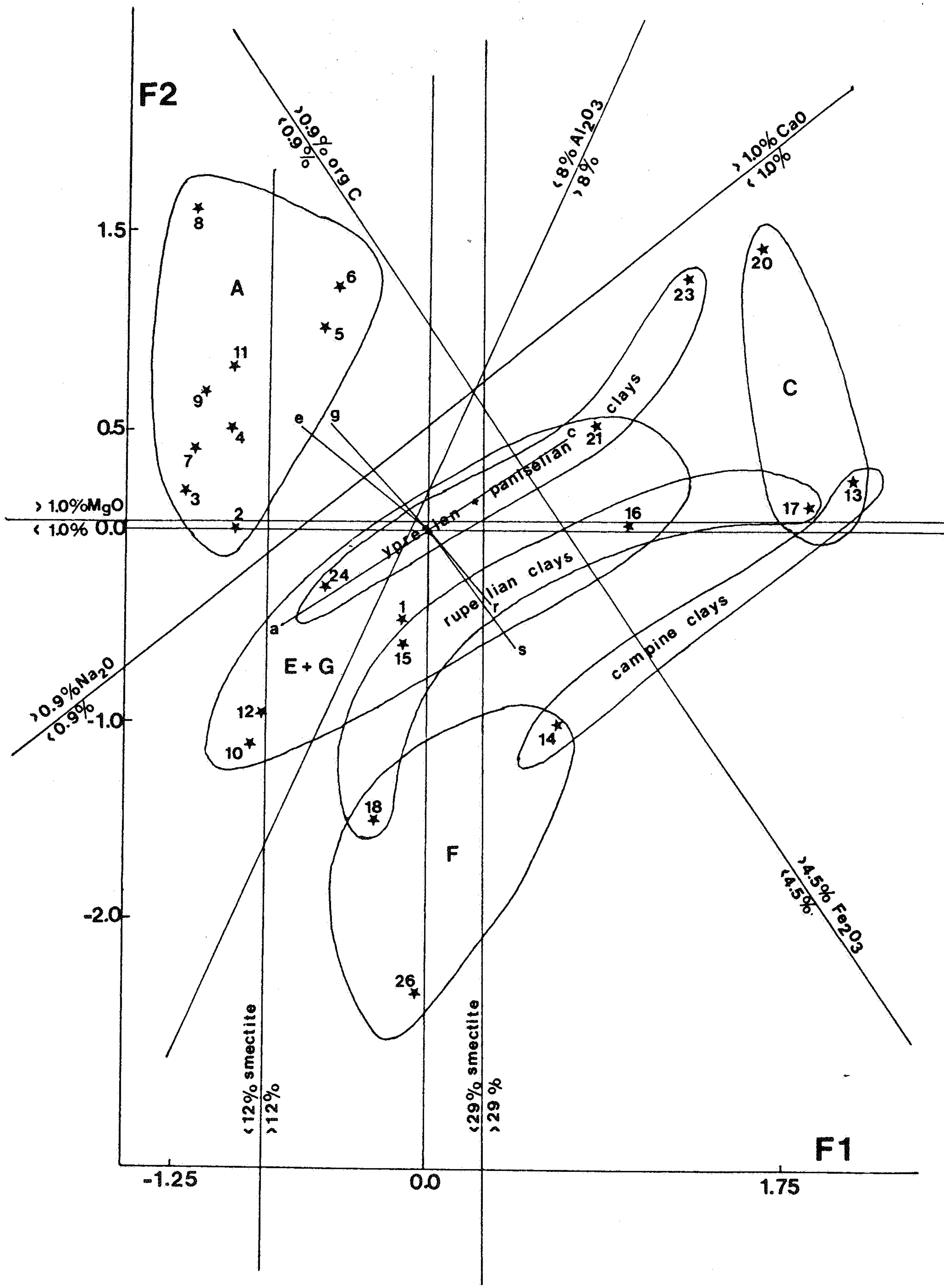


Figure 6 : Distribution of the clusters on F2*F1 plot and subdivision of the samples based on seven variables.

Sample number (ref. table 1)	Factor 1	Factor 2	Factor 3	Factor 4
1	-0.1164	-0.5283	0.3039	0.1648
2	-0.9650	0.0419	-0.2191	-0.7489
3	-1.2071	0.1689	-0.1047	-0.6389
4	-0.9337	0.5171	-0.3785	-0.2890
5	-0.4943	1.0229	0.3008	-0.0638
6	-0.4550	1.1962	0.4168	0.1760
7	-1.1490	0.3759	0.3466	-0.0282
8	-1.1330	1.5657	1.2622	0.8041
9	-1.0641	0.6807	0.5661	0.3235
10	-0.8475	-1.0854	-0.2264	-0.0924
11	-0.9161	0.7554	0.9881	0.2500
12	-0.7900	-0.9951	-0.3343	-0.2105
13	2.0427	0.2412	0.8276	-1.7406
14	0.6039	-0.9910	0.2354	0.3893
15	-0.1008	-0.5679	-0.2869	-1.5105
16	0.9726	-0.0383	0.4799	0.0248
17	1.9009	0.1200	1.3248	-1.1121
18	-0.2437	-1.4540	-0.5998	-0.0257
19	0.5080	0.0918	-0.0965	2.9189
20	1.5939	1.4498	1.1476	0.2806
21	0.8104	0.4855	-1.3252	-1.0276
22	0.4239	0.0443	-2.2952	0.7560
23	1.2312	1.2720	-2.6326	0.7997
24	-0.4945	-0.2809	-1.2473	-1.3408
25	0.8894	-1.6863	0.5899	0.9112
26	-0.0667	-2.4020	0.9570	0.0300

Table 3 : Principal factor analysis : scores of the samples on four principal factors.

In figure 6 (F1*F2), the Ypresian and Paniselian, respectively the Rupelian, and the Campine clays form threee stretched groups with their length axis perpendicular to the vectors r and s (illite and kaolinite vector). The Campine clays are the most refractory of the three considered groups.

2.3. Canals

In the preceding plots loess, marine, coastal and alluvial clays and silts could not be distinguished as such.

The question may arise if the selection of the measured variables or the way of treating and representing last ones is responsible for this.

By means of the "Canals" program (canonical analysis) nominal variables of the "field" and numerical physico-chemical, mineralogical variables considered above have been treated together in order to obtain canonical groups. As field variables, the stratigraphic position, the sedimentation type and the geographical position of the samples have been selected. These nominal variables have been given a number. The loadings of the variables and the scores of the samples on two new, mathematically created variables are represented respectively in tables 4 and 5, and drafted in figure 7.

Examination of figure 7 representing the plot in the plane determined by the first and second canonical axis of the physico-chemical/mineralogical set proves that these variables allow to make this distinction.

Vector A represents the stratigraphic position, vector B gives additional stratigraphic specifications such as "integral", "lower", "upper", "weathered". Vector C refers to the sedimentary environment ; marine, coastal, alluvial and loess/loam types are considered.

Original variable	C	Canal 1	Canal 2	Communality
SiO2	a	-0.212	0.443	0.241
Al2O3	b	-0.183	-0.431	0.219
Fe2O3 (total)	c	0.212	-0.647	0.464
MgO	d	0.229	-0.026	0.053
Na2O	e	0.305	0.696	0.577
K2O	f	-0.264	-0.499	0.319
CaO rest	g	0.542	0.274	0.369
H2O 105°	h	-0.276	-0.474	0.301
H20 1000°	i	0.196	-0.487	0.276
So4--	j	-0.328	-0.518	0.376
Org. C	k	0.085	-0.731	0.542
F	l	-0.037	-0.289	0.085
PPI	m	-0.266	-0.654	0.498
TSS	n	-0.261	-0.604	0.433
Calcite (cc)	o	0.487	0.254	0.302
Pyrite (py)	p	-0.020	-0.506	0.256
Smectite (sm)	q	-0.257	-0.744	0.620
Illite (ill)	r	-0.275	0.170	0.105
Kaolinite (kaol)	s	-0.413	-0.150	0.193
		variance/variable 0.082	variance/variable 0.246	0.328
Stratigraphical position (rough)	A	-0.754	-0.270	0.641
Stratigraphical position (subdivision)	B	-0.789	-0.337	0.736
Environment of sedimentation	C	0.431	0.893	0.983
Exploitation area	D	0.553	-0.094	0.315
		variance/variable 0.082	variance/variable 0.246	0.328

Table 4 : Canals analysis : loadings, variance and communality estimates related to canal 1 and canal 2. (C = code - figures).

Vector D relates to the geographic position of the samples.

Figure 7 shows an arrangement of the samples according to the sedimentary environment (vector C). The groups of loess/loam and alluvial materials are relatively dense and well separated from each other.

Figure 8 shows the approximate linear spreading of the samples belonging to cluster A. The value of 0.8 % Na_2O is taken as the borderline between the field with the samples of cluster A and the field with all the other samples. Within cluster A the alluvial clays are distinguished from the loess/loam materials by their higher smectite content ; the coastal clays differ from the alluvial clays especially by their MgO and organic C as well as their lower SiO_2-content.

Compared with the coastal clays, the marine clays - showing also an almost linear dispersion - demonstrate relative high figures for organic carbon and pyrite, and a high ratio smectite : illite. These lineations cross nearly perpendicularly vector C (sedimentary environment).

The stretched cloud of marine clays (fig. 8) can be subdivided in three zones :

- a left zone with the weathered Wijer clay (18), the Paniselian clay (22) (impoverished in organic C and pyrite by oxidation) and the sandy Ypresian material (24) ;

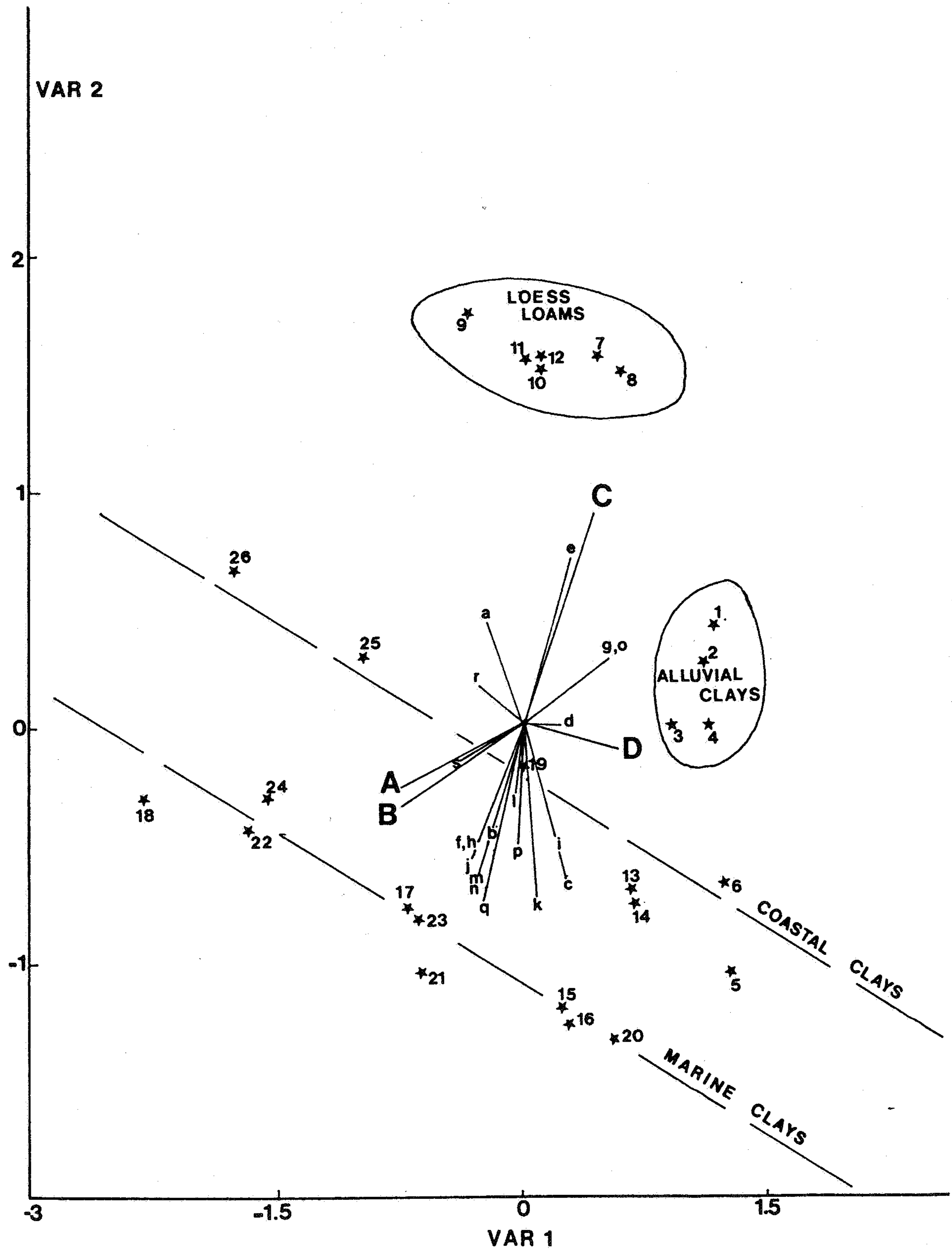


Figure 7 : Canals analysis : loadings of the "field", the physico-chemical and mineralogical variables, together with the scores of the samples on canal 1*canal 2 plot. Subdivision of the samples based on their sedimentary environment.

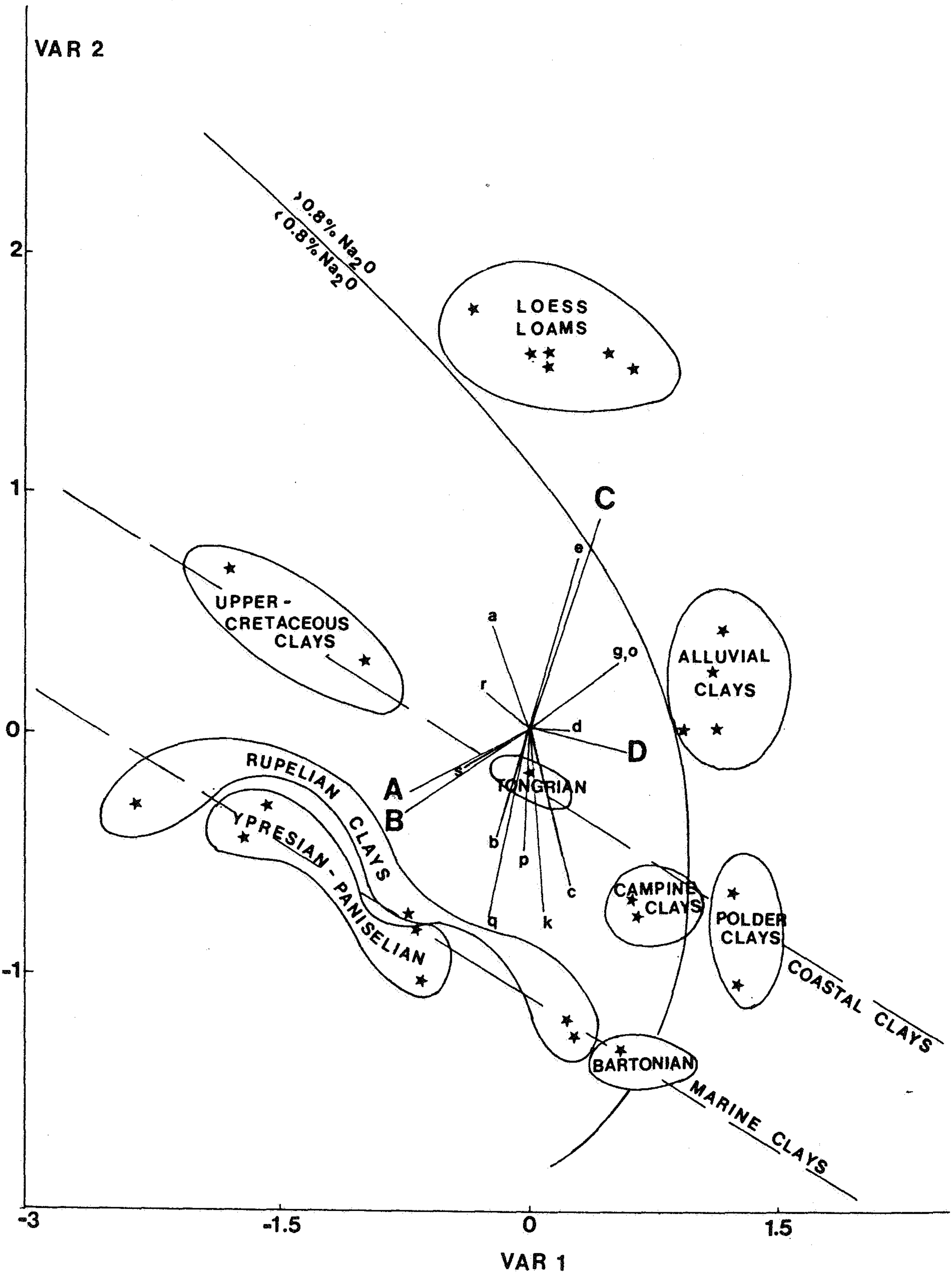


Figure 8 : Canals analysis : as fig. 7, but the samples grouped according to their geological age as well as to their sedimentary environment.

- a central zone with the Rupelian (17), Ypresian (23) and Paniselian (21) clays, characterized by their high content in water soluble sulfates (≅0.8 % $SO_4^=$) ,

- a right subgroup, consisting of the Rupelian (15) (16) and Bartonian (20) clays, distinct by reason of their combination of intermediate $SO_4^=$ content (≤ 0.3 %) with high values for pyrite.

Figure 8 also shows the considerable dispersion of materials belonging to a same stratigraphic formation, especially within marine deposits.

The geomorphological constitution of the area of sedimentation, the climatological circumstances at the time of deposition, the (in)stability of the sedimentary environment, possible changes of source area of the detrital material, as well as alteration processes after sedimentation (e.g. oxidation, lixivation, bioturbation, cryoturbation) determined the final outlook, as well as the mineralogical and chemical composition of the sediments. For loess deposits the period of sedimentation was relatively short and the source area remained almost unchanged. Loess deposits have been partly decalcified and delivered loams. The alluvial silts are, geologically spoken, of recent date. The formation of coastal and marine deposits covered a much longer period of time ; they show partly for this reason a greater variability in deposited material.

The stretched groups of coastal and marine clays and silts lay almost parallel with vector D, which represents the geographic position of the samples. In the group of coastal clays there exists a geographic arrangement from east to west (reversed sense). This arrangement corresponds with a sequence from older (cretaceous) towards younger (Holocene) sediments. With the group of marine clays such an arrangement does not exist.

1cm'

S.	Canal 1	Canal 2
1	1.187	0.410
2	1.109	0.238
3	0.916	-0.014
4	1.137	0.001
5	1.279	-1.074
6	1.219	-0.680
7	0.487	1.559
8	0.595	1.494
9	-0.324	1.746
10	0.121	1.527
11	0.053	1.543
12	0.131	1.555
13	0.647	-0.722
14	0.641	-0.772
15	0.252	-1.220
16	0.308	-1.274
17	-0.727	-0.788
18	-2.300	-0.316
19	-0.001	-0.187
20	0.566	-1.310
21	-0.614	-1.052
22	-1.686	-0.452
23	-0.666	-0.834
24	-1.562	-0.320
25	-0.979	0.290
26	-1.787	0.651

Table 5 : Canals analysis : scores of the samples on canal 1 and canal 2.
: P.S. = Sample number (ref. table 1).

3. CONCLUSIONS

The results of the statistical treatment on 26 clays and loams demonstrate the great influence of the sedimentary environment on the physico-chemical and mineralogical variables of a clay or silt, especially on Na_20, Al_2O_3, Fe_2O_3, smectite, pyrite and organic carbon (fig. 8).

The "Canals" method offers the opportunity to delineate in a two-dimensional diagram the loess/loam, the alluvial, the coastal and the marine clays as distinct groups, based on physico-chemical and mineralogical data.

The fact that superficially weathered clays take a position completely different of that occupied by their unweathered equivalents, illustrates the importance of the weathering process.

No straight relationship has been found between the physico-chemical and mineralogical variables on the one hand and the geographic position of the clays and silts on the other.

The graphical representation of the results of the canonical analysis illustrates in a rather compact way the relations between all the variables considered.

ACKNOWLEDGMENTS

The authors are grateful to Mrs M. Wauters-Vuylsteke for her advice on the possibilities of the SAS-packages.

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Manuscrit received on 20 December 1990 and accepted for publication on 18 November 1991.