Clays and Clay Minerals, Vol. 36, No. 3, 277–283, 1988.

STATISTICAL ANALYSIS OF CLAY MINERAL ASSEMBLAGES IN FAULT GOUGES

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Abstract—The clay mineral distributions in fault gouges from shear zones in several slates, phyllites, mica schists, and gneisses of the Eastern Alps were statistically analyzed for consistencies in their occurrence. Discriminant analyses suggested significant groupings of the most common minerals: illite, smectite, kaolinite, and chlorite. The clay mineral distributions in the fault gouges appeared to be related to regional geological units. No relationship, however, was found with the piles of nappes of the Alps. The influence of the mineralogical composition of the parent rock on the clay mineral assemblages appeared to be minor, but the shear behavior of the parent rocks, which is mainly a function of rock strength, was found to control the formation of the clay minerals. In hard rocks (e.g., gneisses), solution transfer at an early stage of the shear process was apparently extensive enough to favor kaolinite formation. As shearing continued, the rate of solution transfer gradually decreased and favored the formation of smectite. In softer rocks (e.g., phyllites), the extent of solution transfer during the shear process was less than in the gneisses and generated an environment that favored smectite formation, even during the early stages of shearing.

Key Words—Chlorite, Discriminant analysis, Fault gouge, Illite, Kaolinite, Shearing, Smectite, Solution transfer.

Zusammenfassung—Die Tonmineralverteilungen toniger Mylonite aus Scherzonen in Tonschiefern, Phylliten, Glimmerschiefern, und Gneisen der Ostalpen wurden statistisch auf Gesetzmäßigkeiten ihres Auftretens untersucht. Die Diskriminanzanalyse zeigt, daß eine signifikante Gruppenbildung mittels der am häufigsten auftretenden Minerale Illit, Smectit, Kaolinit, und Chlorit möglich ist. Es besteht eine Abhängigkeit zwischen den Tonmineralverteilungen in den Myloniten und regionalgeologischen Einheiten. Eine Beziehung zu den alpinen tektonischen Deckenstockwerken ist nicht erkennbar. Die mineralogische Zusammensetzung des Ausgangsgesteins hat nur untergeordneten Einfluß auf die Tonmineralassoziationen. Dagegen steuert das Scherverhalten der Ausgangsgesteine, das im wesentlichen von der Gesteinsfestigkeit abhängt, die Tonmineralneubildungen. In Gesteinen mit hoher Scherfestigkeit (z.B. Gneisen), erreicht zu Beginn der Scherverformung die Lösungswegsamkeit ein Ausmaß, das Kaolinitbildung begünstigt. Im weiteren Verlauf der Scherdeformation nimmt die Lösungswegsamkeit allmählich ab. Dies führt zur bevorzugten Bildung von Smectit. In Gesteinen mit geringerer Scherfestigkeit (z.B. Phylliten) ist die Lösungswegsamkeit bei der Scherdeformation kleiner als in Gneisen, sodaß ein Milieu entsteht, das schon zu Beginn der Scherdeformation die Bildung von Smectit begünstigt.

INTRODUCTION

Fault gouge is a product of tectonic grinding. Low-temperature solution transfer during and/or after tectonic action leads to the alteration of the parent rock and to the formation of clay minerals, especially if silicate rocks are involved. The distribution of clay minerals is controlled by the physicochemical environment present during the alteration process. Thus, the clay mineral composition of fault gouges is a strong indication of the conditions that prevailed during their formation (Wu *et al.,* 1975; Wu, 1978; Riedmüller, 1978). Likewise, the mechanical behavior of the gouge is greatly dependent on its clay mineral composition. Bjerrum *et al.* (1963), Brekke and Howard (1973), and Riedmüller and Schwaighofer (1977) gave evidence of the correlation of fault gouges containing smectite with roof falls and failure in tunnel construction. Experimental work by several authors has shown the shear behavior of filled discontinuities to be controlled by the clay content and clay mineral composition (e.g., Shimamoto and Logan, 1981; Müller-Vonmoos *et al.,* 1981; Sonderegger, 1985; Höwing, 1984; Höwing and Kutter, 1985).

These studies therefore prompt the engineering geologist to ask about the factors that control the nature of the clay mineral assemblages in fault gouges: namely, is the parent rock an influential factor; do differences exist among the various geological units as to the presence and composition of clay minerals; and what is the influence of the tectonic development of the fault zone? To answer the above questions, a statistical study was performed on a great number of clay mineral data from

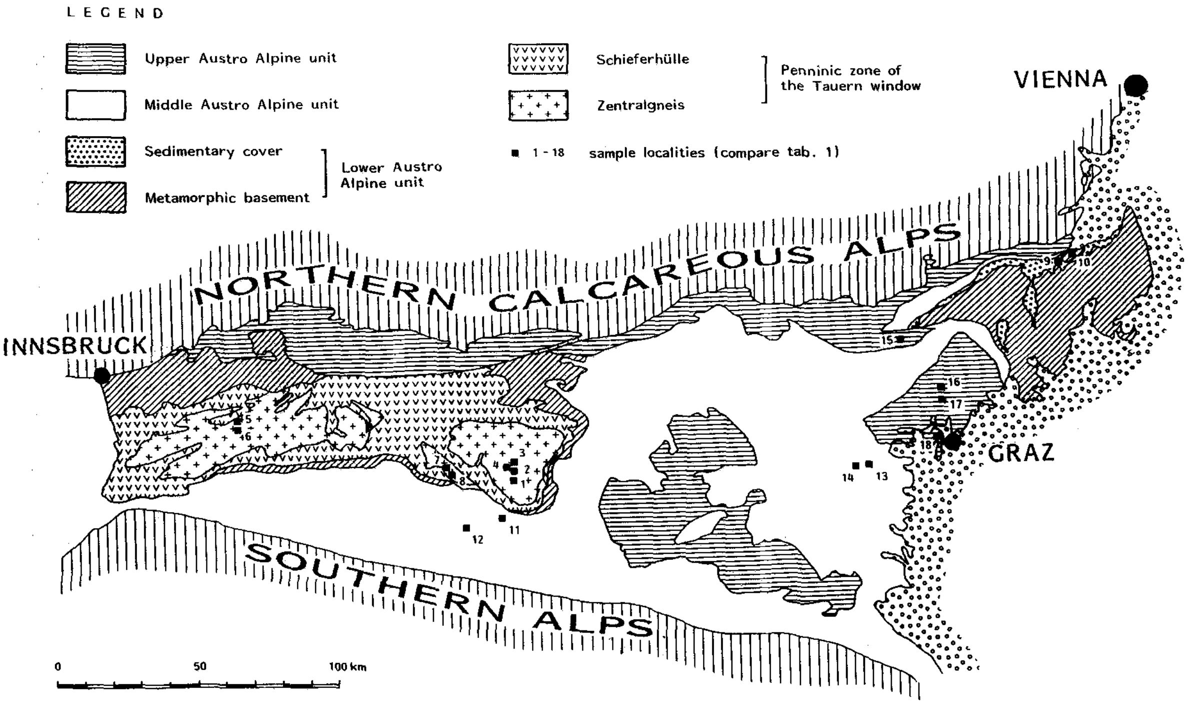

Figure 1. Simplified geological map of the Eastern Alps showing sample localities.

fault gouges from the central and eastern parts of the Eastern Alps.

MATERIALS AND METHODS

Samples came from tunnels of hydroelectric projects, road tunnels, and other deep underground excavations, in which near-surface weathering was essentially absent. The material tested comprised 247 gouge samples from various tectonic units and primary rocks. Sample locations and parent rocks are identified in Figure 1 and Table 1. The particle size distribution of fault gouges showed an extremely heterogeneous pattern. The proportion of clay in the bulk sample varied between 0.2 and 20%. Common nonclay minerals in the clay fraction were quartz and feldspar; carbonates were rare. The particle sizes of the samples were determined by wet sieving and by the sedimentation method. The <2-μm size fraction of each sample was analyzed for its phyllosilicate distribution by X-ray powder diffraction (XRD) following the methods described by Jackson (1956) and Whittig (1965). The relative amount of clay minerals was estimated semiquantitatively on the basis of the intensities of basal reflections observed on samples with preferred orientations (Johns *et al.*, 1954).

The statistical analysis, including the overall representation of data, was based chiefly on multivariate classification procedures, with the emphasis being on linear discriminant analysis (Davis, 1973; Le Maitre, 1982), using the BMDP statistical software package (Dixon, 1983). Univariate elementary statistics describe the individual groups of the statistically most significant group formation.

RESULTS

The objective of the statistical analysis was to classify the samples according to their regional-tectonic settings and lithological composition by means of multivariate statistics. By this procedure all samples under consideration were arranged into meaningful groups that allowed interpretation in a regional-tectonic and/or lithologic sense. Generally, samples were classified: (1) by means of statistics followed by meaningful geological interpretations of that statistical classification; and (2) according to geological features using statistical proofs of that geological classification.

Initially, the general distributions of the clay minerals were characterized by elementary statistics. Four minerals, illite, smectite, chlorite, and kaolinite, accounted for more than 98% of all 247 samples. Mixed-layer minerals and vermiculite were rare (cf. Figure 2 and Table 2). A fact of interest to the engineering geologist was the common occurrence of smectite, a mineral having poor mechanical properties. Smectite was identified in more than 80% of the samples, some of which contained as much as 20%.

The histogram of illite (Figure 3) shows a bimodal distribution with a greater portion of higher contents. The distributions of smectite, chlorite, and kaolinite show a strong negative skewness due to the many zero values and the generally lower percentages, as com-

Table 1. Locality, alpine tectonic unit, geological unit,[1] and parent rock of samples.

Sample locality	Number of samples	Project	Alpine tectonic unit	Geological unit	Parent rock
1	10	KW-Malta Hattelberg gallery	PE	Tauern window, Zentralgneis	gneisses
2	7	Göss gallery	PE	Tauern window, Zentralgneis	gneisses
3	3	Malta gallery	PE	Tauern window, Zentralgneis	gneisses
4	6	Samer-Ritter gallery	PE	Tauern window, Zentralgneis	gneisses
5	5	KW-Zillergründl Überleitung Nord	PE	Tauern window, Zentralgneis	gneisses
6	4	dam foundation	PE	Tauern window, Zentralgneis	gneisses
7	11	KW-Fragant Zirknitz gallery	PE	Tauern window, Zentralgneis	gneisses
8	8	Oschenik gallery	PE	Tauern window, Zentralgneis	gneisses
9	40	Semmering Schnellstraße exploratory drillings for highway tunnel	LAA	Semmering complex, metamorphic basement	phyllites
10	29	Semmering Schnellstraße exploratory drillings for highway tunnel	LAA	Semmering complex, sedimentary cover	slates
11	7	KW-Fragant Wölla gallery	MAA	Kreuzeck complex, metamorphic basement	mica schists (and gneiss)
12	16	Draßnitzbach gallery	MAA	Kreuzeck complex, metamorphic basement	mica schists (and gneiss)
13	17	Südautobahn Herzogberg highway tunnel	MAA	Koralpe complex, metamorphic basement	gneisses
14	20	Kalcherkogel highway tunnel	MAA	Koralpe complex, metamorphic basement	gneisses
15	30	Semmering Schnellstraße Niklasdorf highway tunnel and cut	UAA	Styrian Grauwackenzone	phyllites
16	16	KW-Rabenstein dam foundation	UAA	Paleozoic of Graz	phyllites
17	13	KW-Peggau Deutsch-Feistritz exploratory drillings for dam foundation	UAA	Paleozoic of Graz	chlorite-phyllites
18	5	Plabutsch highway tunnel	UAA	Paleozoic of Graz	chlorite-phyllites

PE = Penninic zone; LAA = Lower Austro Alpine unit; MAA = Middle Austro Alpine unit (*sensu* Tollmann, 1959); UAA = Upper Austro Alpine unit.

[1] As represented in Figure 1.

pared with illite (see Figure 3). Automatic multivariate classification procedures (cluster algorithms, R- and Q-mode factor analysis), made on the bulk data, yielded no geological or lithological grouping of the samples, because of the non-normal distributions of the variables. Therefore, the samples were grouped in various manners according to geological features, such as sampling localities and/or lithological and tectonic properties (cf. Table 1).

These different group formations were tested statistically by means of discriminant analysis, which discriminates in an optimal fashion among two or more predefined groups of samples. The method of stepwise linear discriminant analysis (Jennrich, 1977) computes a set of linear classification functions by selecting the most discriminating variable among the groups at each step; similarly, a variable will be deleted if its discriminatory power becomes too low. In addition, canonical variables are computed that are composed of coefficients of the original variables and a constant. These canonical variables are the coordinate axes of a multidimensional sample space and allow optimal separation among the sample groups (Reyment *et al.*, 1984). The efficiency of the method depends heavily on the data structure of the predefined groups of samples (Krzanowski, 1977).

The arrangement in Table 3, which includes seven groups of samples (cf. Table 1) yielded the best results. Table 4 shows the results of the discriminant analysis for the seven groups. The most important discriminating variables were found to be kaolinite, smectite, mixed-layer minerals, and illite, as indicated by high F-values, i.e., high discriminatory power. Chlorite appeared to be of minor importance. Separation among the seven groups was satisfactory according to the F-values of the analysis of variance, except for the differences between groups A and B and B and D. In general, more than 60% of all samples were classified in their geologically predefined group. Groups C (76%) and E (73%) displayed the highest proportions of correctly classified samples. The classification matrix contained the classification pattern of all samples in relation to the seven groups. The coefficients of the two most powerful canonical variables are also listed in Table 4.

Positions of and relations among the seven groups are shown in the discriminant model of Figure 4, based on group separation in a two-dimensional system

Table 2. Basic statistics for the phyllosilicates (<2 μm) from all 247 samples.

	Mean	Standard deviation	Coefficient of variation	Zero values
Illite	49.0	26.7	0.5	3
Smectite	24.9	27.0	1.1	41
Chlorite	18.4	19.1	1.0	68
Kaolinite	5.9	13.6	2.3	173
Mixed-layer	1.5	8.1	5.4	223
Vermiculite	0.2	1.5	8.9	243

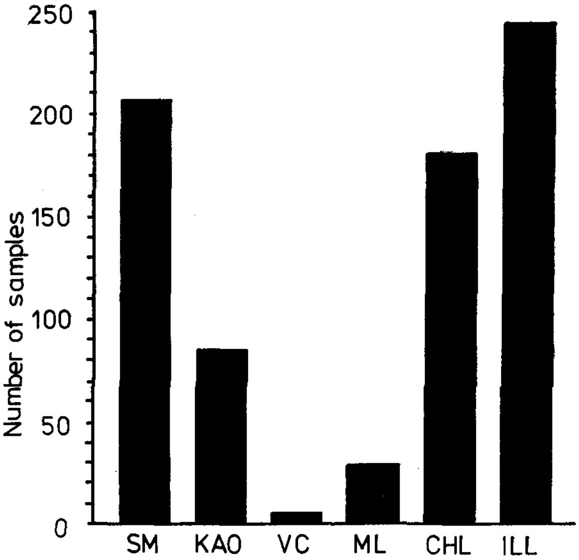

Figure 2. Distribution of smectite (SM), kaolinite (KAO), vermiculite (VC), mixed-layer mineral (ML), chlorite (CHL), and illite (ILL) of the 2-μm clay fraction from all 247 samples.

formed by the two most powerful canonical variables. More than 75% of all samples in each group are enclosed by the group separation lines, except group E, which shows greater dispersion. The positions of the groups in this graph indicate very distinct settings for groups C, F, and G in the outer parts of the diagram. In contrast, groups A, B, and D show some overlap. Increasing values on the x-axis (first canonical variable) correspond mainly to increasing percentages of kaolinite, smectite, and mixed-layer minerals; increasing values on the y-axis (second canonical variable), to decreasing percentages of illite and increasing percentages of chlorite. Thus, the grouping pattern could be checked with respect to these four minerals.

Before proceeding to the statistical proof of the proposed grouping shown in Table 3, a closer look at the individual groups is essential. Table 5 and Figure 5 give the elementary statistics and histograms of the constituent clay minerals from the seven regional-lithological groups listed in Table 3. Mean compositions and variations of the groups as reflected also by the generally small coefficients of variation for the most abundant clay minerals are indicative of the specific mineralogical characteristics and special features of each group.

The principal data relating to the histograms of Figure 4 are summarized in Table 6. As evidenced by the shapes of the histograms, the majority of the variables in the different groups are normally distributed. The negatively skewed histograms, especially those of smectite (group D), chlorite (group E), and kaolinite (group D) indicate the log-normal distributions of these minerals. Multimodal distributions reflect different sample localities in groups C (smectite) and G (illite, kaolinite). In general, the percentages and distributions of the constituent clay minerals agreed very well with the differences among the seven groups as found by the classification of the linear discriminant model.

DISCUSSION

The distribution patterns of the groups shown in Figure 4 suggest a close relationship of clay mineral

Table 3. Grouping of fault-gouge samples as proved by discriminant analysis.[1]

Statistical group	Localities	Alpine tectonic unit	Geological unit	Parent rock
A	9	LAA	Semmering complex, metamorphic basement	phyllites
B	15	UAA	Styrian Grauwackenzone	phyllites
C	10	LAA	Semmering complex, sedimentary cover	slates
	16	UAA	Paleozoic of Graz	phyllites
D	11, 12	MAA	Kreuzeck complex, metamorphic basement	mica schists (and gneiss)
E	13, 14	MAA	Koralpe complex, metamorphic basement	gneisses
F	17, 18	UAA	Paleozoic of Graz	chlorite-phyllites
G	1–8	PE	Tauern window, Zentralgneis	gneisses

[1] For sample localities, see Table 1 and Figure 1.

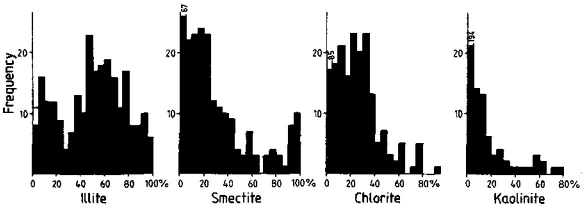

Figure 3. Frequencies (f) of illite, smectite, chlorite, and kaolinite in percentages from all 247 samples.

assemblages to geological units, which in fact constitute regional geological units defined by their largely uniform geological developments within the piles of nappes of the Alps (Penninic zone, Lower Austro Alpine unit, Middle Austro Alpine unit, Upper Austro Alpine unit). No relationship with the piles of nappes themselves has been detected (Table 3). The dependence of group formation on these geological units may be explained by the influence of local tectonics on clay mineral formation in fault zones. According to Riedmüller (1978), variations in the environment of faults give rise to a consistent zoning of clay mineral assemblages. Obviously, similar laws may be postulated for geological units having reached different stages of tectonic development.

Another, although weaker, factor controlling group formation is parent rock composition. Wu (1978) concluded from data presented by Brekke and Howard (1973) and Wahlstrom *et al.* (1968) that different parent rocks give rise to fault gouges having similar clay

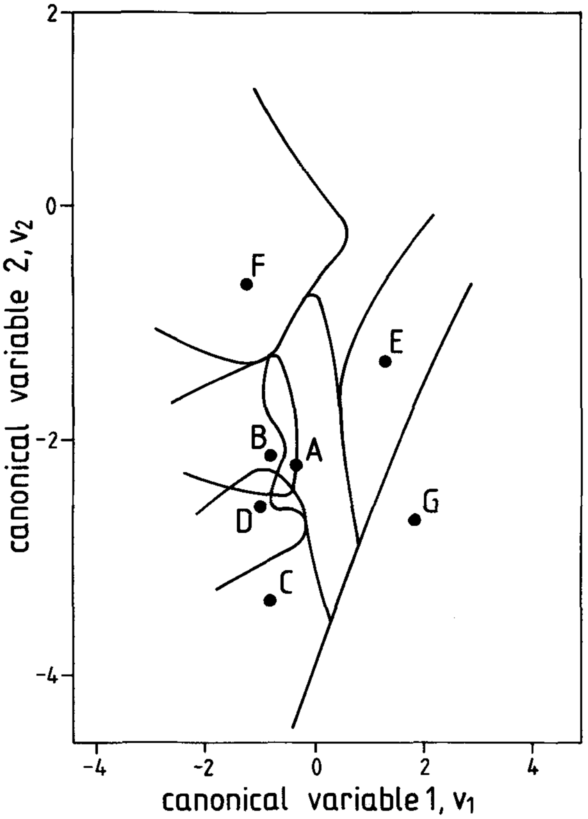

Figure 4. Discriminant model showing the distribution of groups A–G in relation to the first (V_1) and second (V_2) canonical variable; (cf. Table 4).

Table 4. Main results from the discriminant analyses, showing optimal separation among the seven groups A–G (see Table 3) based on five clay minerals using canonical variables.

Discriminant variables with F-values		ill 1.97	sm 2.23	chl 1.41	kao 2.37	ml 2.09	$F_{95\%}$ = 2.14		
F-matrix of group separation:		A	B	C	D	E	F		
	B	1.77							
	C	6.97	6.97						
df = 5.236	D	3.12	0.66	5.15					
$F_{99\%}$ = 2.89	E	11.13	17.83	29.45	19.42				
	F	10.62	5.67	21.34	7.09	23.61			
	G	22.99	23.90	35.79	19.44	18.91	31.43		
% of correctly classified samples:		A	B	C	D	E	F	G	Total
		50	57	76	61	73	67	50	61
		Number of cases classified into group							
Classification-matrix		A	B	C	D	E	F	G	
	A	20	5	8	1	3	3	0	
	B	5	17	3	1	0	3	0	
	C	4	3	34	4	0	0	0	
	D	0	3	3	14	0	2	1	
	E	1	0	2	0	27	6	1	
	F	0	2	3	0	1	12	0	
	G	2	0	9	3	11	2	17	

Canonical variables:

$V_1 = 0.076\ \text{ill} + 0.114\ \text{sm} + 0.067\ \text{chl} + 0.147\ \text{kao} + 0.122\ \text{ml} - 8.866$

$V_2 = -0.096\ \text{ill} - 0.059\ \text{sm} - 0.033\ \text{chl} - 0.088\ \text{kao} - 0.092\ \text{ml} + 7.454$

ill = illite; sm = smectite; chl = chlorite; kao = kaolinite; ml = mixed-layer minerals.

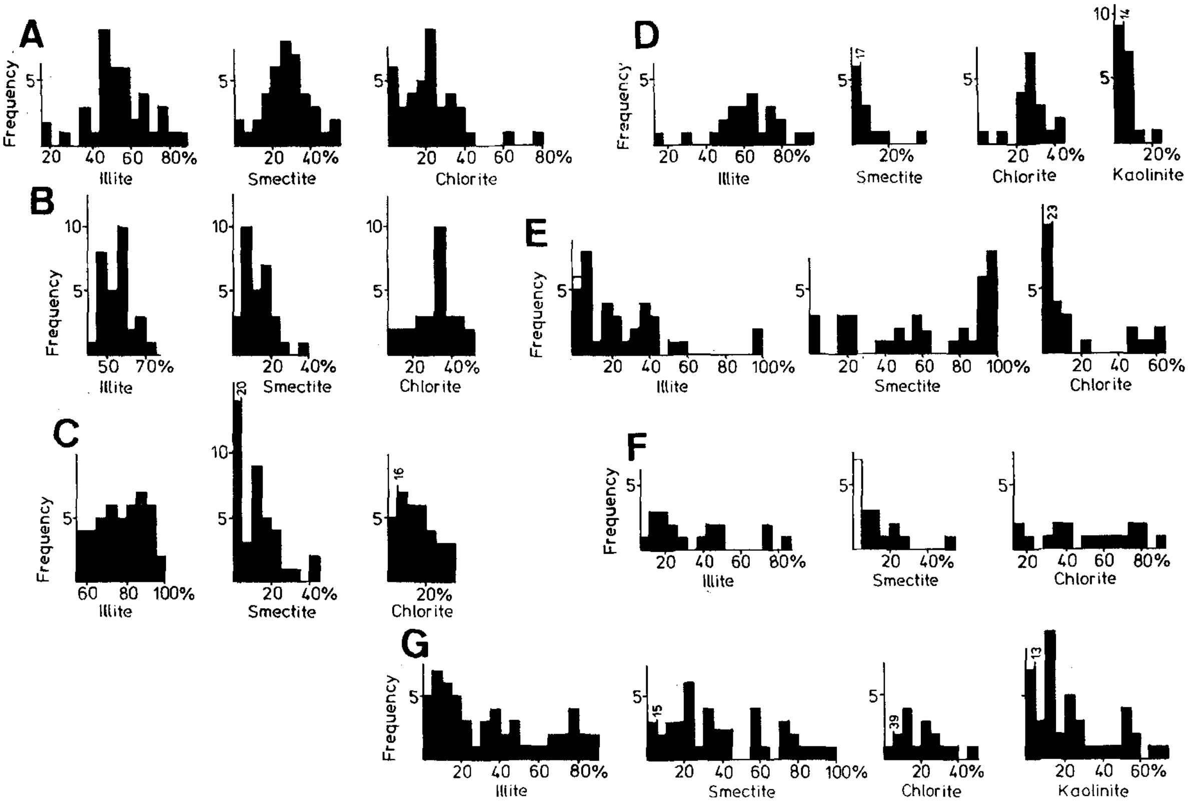

Figure 5. Frequencies of the constituent phyllosilicates (<2 μm) in groups A–G; numbers in the left bar indicate zero values; (cf. Figure 3).

mineral distributions. Indeed, our own attempts to find clay mineral groupings according to parent rock types failed at first. Figure 4, however, suggests some dependence of the clay mineral assemblages on the nature of the parent rock. The clear distinction between groups C and F may be a result of the high illite and chlorite contents of the parent rock (Table 5).

The strength properties of the parent rocks also ap-

Table 5. Distribution of the phyllosilicates (<2 μm) from the seven groups A–G.

		Group						
		A (n = 40)	B (n = 30)	C (n = 45)	D (n = 23)	E (n = 37)	F (n = 18)	G (n = 45)
Illite	x	51.7	55.6	78.4	62.0	24.0	36.8	34.5
	s	15.2	7.6	12.0	17.8	24.2	23.8	27.8
	C	0.3	0.1	0.2	0.3	1.0	0.8	0.6
Smectite	x	27.0	12.9	10.2	4.1	62.2	10.5	30.7
	s	12.4	8.1	10.4	8.3	33.6	13.1	29.3
	C	0.5	0.6	1.0	2.0	0.5	1.3	1.0
Chlorite	x	21.3	29.7	10.7	28.3	11.6	51.7	5.9
	s	16.4	10.9	10.1	10.4	19.9	24.2	11.3
	C	0.8	0.4	0.9	0.4	1.7	0.5	1.9
Kaolinite	x	tr	1.7	0.5	4.4	2.1	—	22.1
	s	—	4.3	1.4	4.6	10.6	—	21.1
	C	—	2.5	3.0	1.0	5.0	—	1.9
Mixed layer	x	tr	0.2	0.1	1.5	—	—	6.1
	s	—	0.6	0.3	5.9	—	—	16.7
	C	—	3.5	3.2	3.9	—	—	2.7

n = number of samples, x = arithmetic mean, s = standard deviation, C = coefficient of variation, tr = very rare occurrence.

Table 6. Histogram configurations for the mineral distributions in groups A–G as shown in Figure 5.

	Gaussian	Negatively skewed	Multimodal	Uniform
Illite	A, B, C, D, F	E	G	—
Smectite	A, B, G	D, F	C, (E)	—
Chlorite	A, B, D, G	C, E	—	F
Kaolinite	—	D	G	—

pear to affect group formation. Thus, Figure 4 suggests a linear arrangement of soft rocks (slates and phyllites) and hard rocks (gneisses) (canonical variable 1, V_1). Hard rocks react to shear by higher dilatancy values than do soft rocks (Lama and Vutukuri, 1978a, 1978b; Obert *et al.*, 1976). As shearing proceeds, dilatancy, which strongly influences solution transfer in shear zones, gradually decreases after having reached a maximum value (Mandl *et al.*, 1977). The results obtained to date in the present work from clay mineral analyses in fault gouges suggest that during the early stage of the shear process, dilatancy and, hence, solution transfer reached such a degree that the formation of kaolinite was favored as a result of ion removal. As the shearing proceeded, the rate of solution transfer decreased so as to cause an increased metal ion concentration, which led to the formation of illite and, finally, of montmorillonite (Riedmüller, 1978). In contrast, in the softer slates and phyllites, dilatancy and solution transfer during shear-zone development never reached values that were high enough to allow the formation of kaolinite. Even at the beginning of shear-zone development the lower rate of solution transfer present in the softer rocks appears to have generated a chemical environment that favored the formation of illite and montmorillonite.

ACKNOWLEDGMENTS

The research was funded by grants from the Austrian "Fonds zur Förderung der wissenschaftlichen Forschung" (FFWF project nr. P5594). Thanks are due to the Austrian electricity companies Kelag, ÖDK, TKW, Steweag, and Steg, as well as to the Styrian government, for assistance in the sampling.

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(Received 16 May 1987; accepted 30 November 1987; Ms. 1672)