

# Mineralogical and chemical evolution of white micas and chlorites, from diagenesis to low-grade metamorphism; data from various size fractions of greywackes (Middle Cambrian, Morocco)

E. WYBRECHT, J. DUPLAY, A. PIQUÉ, AND F. WEBER

Institut de Géologie et Centre de Sédimentologie et de Géochimie de la Surface, 1 rue Blessig, 67084 Strasbourg Cedex, France

**ABSTRACT.** Four size fractions have been separated and studied in eight samples of Cambrian greywackes, ranging from non-metamorphic to low metamorphic grade. Chemical study included analyses of each size fraction and comparison with the whole rock analysis. Mineralogical study involved analyses of individual crystals using microprobe ( $> 6 \mu\text{m}$ ) and STEM ( $< 6 \mu\text{m}$ ). This showed that in each fraction, a progressive homogenization of the mineralogical composition occurred during the development of metamorphism; that chemical transfers especially of Fe-Mg and K-Na, occurred between fine and coarse fractions and that recrystallization in fine and coarse fractions was simultaneous.

**KEYWORDS:** mica, chlorite, diagenesis, metamorphism, greywackes, Morocco, Cambrian.

THE very low-grade metamorphism (Winkler, 1976) and the pre-metamorphic (diagenetic) evolution of argillites and shales are now well documented (e.g. Kubler, 1964, 1966, 1968; Dunoyer de Segonzac, 1969; Frey, 1970, 1978; Kisch, 1980). On the other hand, little work has been done (McDowell and Elders, 1980; Nicot, 1981) on the evolution of detrital minerals of larger size during very low-grade metamorphism. The present note describes a study of different size fractions separated from rocks that have undergone very low-grade metamorphism.

The rocks which were studied are from the Cambrian 'Schistes à Paradoxides' formation of northwestern Morocco (fig. 1). During the Lower and Middle Palaeozoic this zone constituted a stable platform, which suffered only mild deformation during the Hercynian orogeny, except on its eastern margin, where a deep-seated shear zone was located (Piqué, 1979; Piqué *et al.*, 1980).

Metamorphic evolution is not easily perceptible in this region, except in its eastern part. The largest detrital minerals rarely show evidence of recrystal-

lization, while the clay-size fraction is not visible under the optical microscope. Consequently, as in other non-metamorphosed or weakly metamorphosed series (Kisch, 1980; Parker *et al.*, 1983;

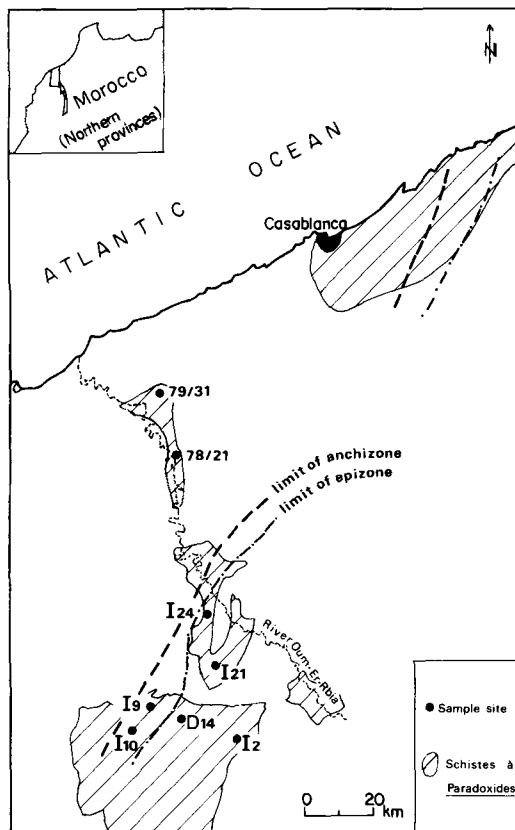


FIG. 1. Location of samples.

Teichmüller *et al.*, 1979; Weber, 1972), metamorphic grade has been determined from the crystallinity of illite in the clay-size fraction ( $< 2 \mu\text{m}$ ) (Weaver, 1960; Kubler, 1964; Dunoyer de Segonzac, 1969). The resulting distribution of the illite crystallinity index shows a coherent regional pattern (fig. 1; Piqué, 1979; Wybrecht, 1984). The series is unmetamorphosed in the west and metamorphic grade increases systematically to low-grade in the east.

Eight samples (fig. 1) representative of the different grades were selected for detailed study. These are constant in lithology (fine-grained greywackes) and in mineralogical and chemical composition, so that comparisons between samples can be made. Samples from the west are undeformed, those from the east are strongly cleaved.

Each of these selected samples was crushed and divided, by sieving and sedimentation, into four size-fractions:  $< 2 \mu\text{m}$ ,  $2\text{--}6 \mu\text{m}$ ,  $6\text{--}50 \mu\text{m}$  and  $> 50 \mu\text{m}$ . Each fraction was studied by X-ray diffractometry and chemical analysis. Separated crystals in each size-fraction have been studied individually, by microprobe analysis and direct optical observation for the largest crystals ( $6\text{--}50 \mu\text{m}$

and  $> 50 \mu\text{m}$ ) and by STEM analyses for the smallest crystals ( $2\text{--}6 \mu\text{m}$  and  $< 2 \mu\text{m}$ ). Analytical procedures and description of the apparatus are given by Duplay (1982) and Wybrecht (1984). Each size fraction of the studied samples is considered as a population of individual minerals. One of the aims of this paper is to describe and define these populations and to compare them within and between samples.

Three triangular diagrams are utilized. (1) The Si-Al-(Fe + Mg) diagram shows the composition of the talc layer. It discriminates between white micas, biotites, and chlorites. (2) The  $(\text{K} + \text{Na} + \frac{1}{2}\text{Ca})\text{--}(\text{Si} + \text{Al})\text{--}(\text{Fe} + \text{Mg})$  diagram expresses the charge of the layer. White micas, biotites, and chlorites occupy separate fields. (3) The Al-Fe-Mg diagram is useful to discriminate between Fe- and Mg-rich chlorites.

#### *The $> 50 \mu\text{m}$ fractions*

*Bulk chemical analysis.* The results of the bulk chemical analyses are presented in Table I as 'proportional ratios'. This ratio represents the abundance of each analysed element in the  $> 50 \mu\text{m}$

TABLE I. Chemical compositions of the different size fractions of analysed samples relative to whole rock composition (WR)

Sample	Si/ Si WR	Al/ Al WR	Mg/ Mg WR	Fe/ Fe WR	Mn/ Mn WR	Ti/ Ti WR	Na/ Na WR	K/ K WR
$> 50 \mu\text{m}$								
78/21	0.97	0.92	0.83	0.81	0.66	0.84	0.87	0.89
79/31	1.14	0.75	0.69	0.95	0.50	0.62	1.09	0.77
I9	1.01	0.99	0.94	0.94	1.33	1.12	0.93	1.02
I10	1.02	1.01	0.95	0.98	3.2	1.11	0.93	1.03
I21	1.09	0.93	0.83	0.87	0.73	1.02	0.89	0.96
I24	1.03	1.01	1	1	1.06	1.1	1.02	0.99
D14	1.01	0.94	0.94	0.87	0.83	0.89	0.89	1.05
I2	1.1	0.875	0.55	0.64	0.66	1.21	1.38	0.97
$6\text{--}50 \mu\text{m}$								
78/21	0.91	1.11	1.27	1.19	1.11	1.03	1.05	1.09
79/31	1.08	0.90	0.88	0.89	0.54	0.93	1.14	0.89
I9	0.89	1.24	1.29	1.31	1.36	1.19	0.87	1.26
I10	0.94	1.11	1.17	1.34	3.47	1.09	0.96	1.09
I21	0.95	1.20	1.02	1.08	1.00	0.84	0.84	1.22
I24	0.96	1.16	1.10	1.07	1.05	0.97	1.13	1.06
D14	0.96	1.14	1.00	0.94	0.80	0.83	0.76	1.31
$2\text{--}6 \mu\text{m}$								
78/21	0.78	1.43	1.90	1.89	1.77	0.95	0.68	1.29
79/31	0.81	1.42	1.43	1.59	1.31	0.85	0.52	1.41
I9	0.75	1.55	1.84	1.94	2.05	0.98	0.54	1.52
I10	0.82	1.44	1.46	1.60	4.63	1.01	0.58	1.63
I21	0.79	1.57	0.98	1.01	0.90	0.99	0.36	1.84
I24	0.82	1.41	1.12	1.14	1.05	0.94	0.48	1.47
D14	0.81	1.43	0.97	0.97	0.86	0.90	0.52	1.75
$< 2 \mu\text{m}$								
78/21	0.69	1.63	2.09	2.10	2.37	0.21	0.47	1.49
79/31	0.74	1.51	1.45	1.73	1.27	0.52	0.29	1.50
I9	0.68	1.76	2.07	2.19	2.42	0.72	0.28	1.74
I10	0.72	1.74	1.34	1.43	4.47	0.75	0.32	1.29
I21	0.72	1.68	0.95	1.16	1.11	1.55	0.31	1.78
I24	0.76	1.55	1.08	1.25	0.98	1.09	0.32	1.68

fraction, relative to its abundance in the whole rock. Values of this ratio which are > 1 indicate an excess in this fraction (Si and Ti). Values lower than 1 indicate a deficiency (Al, Mg, Fe, and K). There is no clear correlation between change in proportion of each element and increasing metamorphism.

*Mineralogical analysis.* In the case of white micas few significant differences are perceptible under the microscope between detrital micas from non-metamorphic or metamorphic samples. Besides the fabric change due to the cleavage development (not examined here), one notes the disappearance of undulose extinction, due to lattice reorganization. Likewise, X-ray diffractometry of extracted crystals shows no important changes related to the metamorphic grade of their host rocks. The only noticeable change is the decrease in width of the (001) peak of the micas with increasing grade, similar to the illite crystallinity changes in the < 2 μm fractions. Microprobe analyses of individual crystals show the chemical evolution of the populations (fig. 2a, b, c). White micas from the non-metamorphic samples show a conspicuous compositional range. This dispersion is smaller for the micas from anchimetamorphic (= very low-grade) samples and most of the micas from epimetamorphic (low grade) rocks have the composition of true phengite according to the data of Velde (1967) and Liewig (1981). Increase in metamorphism clearly

reduces the initial chemical variations of the detrital white mica crystals.

In the non-metamorphic samples, detrital phyllosilicates other than white micas are brown pleochroic, lamellar crystals, whose optical properties (birefringence, extinction, and hues) are those of biotites. In the anchimetamorphic samples, some are still brown but others are green, slightly pleochroic barrel-shaped crystals. Optically they are chlorites and they commonly include one or more lamellae of white mica. Chlorites of the epimetamorphic samples have a lenticular shape related to the tectonic fabric (Wybrecht *et al.*, 1983). Their optical properties are similar from one crystal to another.

X-ray diffractometry shows that all these minerals, even the brown lamellar phyllosilicates of the non-metamorphic samples, have a 14 Å basal spacing and they are identified as 'chlorites'. From the non-metamorphic samples to the epimetamorphic ones, the diffractograms obtained on pure extracted mineralogical fractions present increasingly sharp 14 Å peaks, suggesting a progressive regularization of their lattice.

Preliminary data on the chemical composition of these populations of chlorites have been presented elsewhere (Wybrecht *et al.*, 1983). Fig. 3a, b, c largely confirm this initial study. The populations of crystals from non-metamorphic samples are

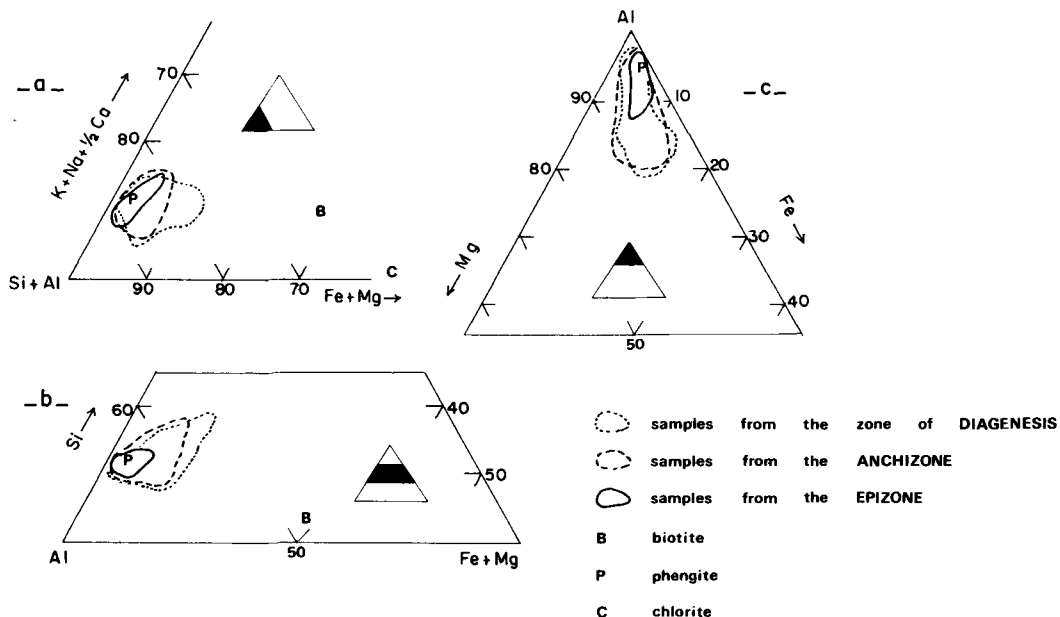


FIG. 2. Mineralogical composition of individual white micas (> 50 μm fractions): B, average biotite; P, average white mica (phengite); C, average chlorite.

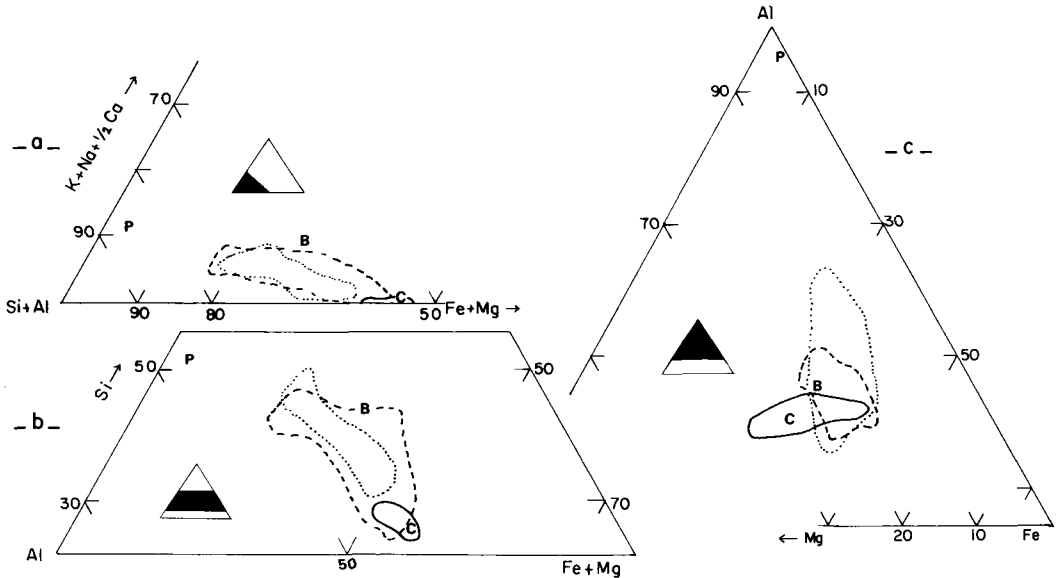


FIG. 3. Mineralogical composition of individual phyllosilicates other than white micas ( $> 50 \mu\text{m}$  fractions). Same symbols and conventions as fig. 2.

chemically intermediate between true white micas, biotites and chlorites. In view of their chlorite structure it can be argued that these minerals were initially detrital biotites, which have partially retained their former composition (e.g.  $\text{K}^+$ ). It is clear that the detail of these structural transformations is poorly understood and needs additional work. The chemical compositions of the non-metamorphic and very low-grade samples are more varied than those of the white micas. As with the micas, this dispersion progressively diminishes as the metamorphism increases and the analysed phyllosilicates become true chlorites in the epimetamorphic samples.  $\text{K}^+$  and other elements, which remain from the former biotite composition and do not find a place in the chlorite lattice, probably enter the lattice of white mica lamellae within the chlorite crystals.

#### The 6–50 $\mu\text{m}$ fractions

**Bulk chemical analysis.** Except for Mn, the proportional ratios of major elements in this fraction (Table I) are close to 1 and it is difficult to find any correlation with metamorphic grade. Si is perhaps a little less abundant in this fraction than in the whole rock.

**Mineralogical analysis.** The largest crystals of this fraction are easily observable under the microscope. It is thus possible to identify both white micas and chlorites, but it is difficult to specify their

optical properties as precisely as in the  $> 50 \mu\text{m}$  fraction.

X-ray diffractometry suggests that these minerals are a mixture of white micas, chlorites, and clay minerals, the latter being more important in the fine part of the fraction. The mixed-layer minerals (14C–14V: chlorite/vermiculite), which commonly occur in the non-metamorphic samples, disappear in the anchi- and epimetamorphic samples.

Following the same procedure as for the  $> 50 \mu\text{m}$  fraction, chemical analyses have been obtained from individual crystals. The results are given in figs. 4 and 5. The dispersion of points representing white micas and chlorites is large for minerals from non-metamorphic samples. This dispersion is considerably reduced as the metamorphic grade increases and the compositions converge to those of true white micas and chlorites.

#### The 2–6 $\mu\text{m}$ fractions

**Bulk chemical analysis.** Analyses of 2–6  $\mu\text{m}$  fractions from seven of the samples, with the same conventions as in the preceding parts of this study, are given in Table I. It is seen that: (i) Si, Ti, and Na are less abundant in the 2–6  $\mu\text{m}$  fraction than in the whole rock, but there is no clear correlation between the amount of this decrease and increasing metamorphism. (ii) In contrast, Al, Mg, Fe, and K are more abundant in this fraction than in the whole rock and the amount of excess Fe

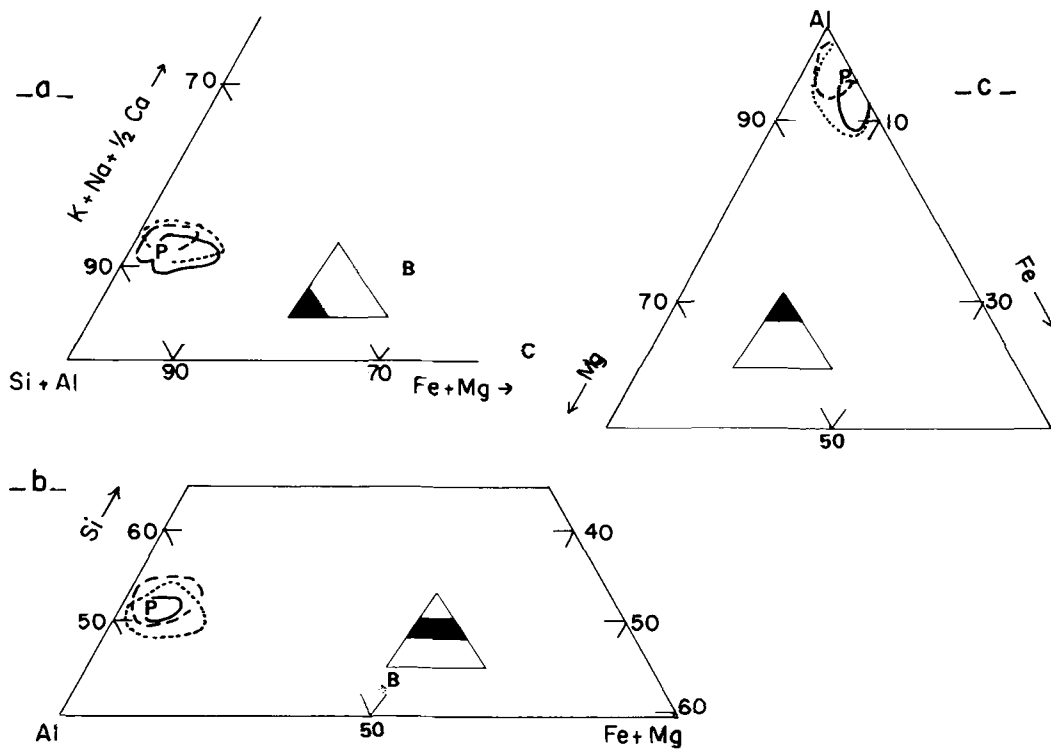


FIG. 4. Mineralogical composition of individual white micas (6-50  $\mu\text{m}$  fractions). Same symbols and conventions as fig. 2.

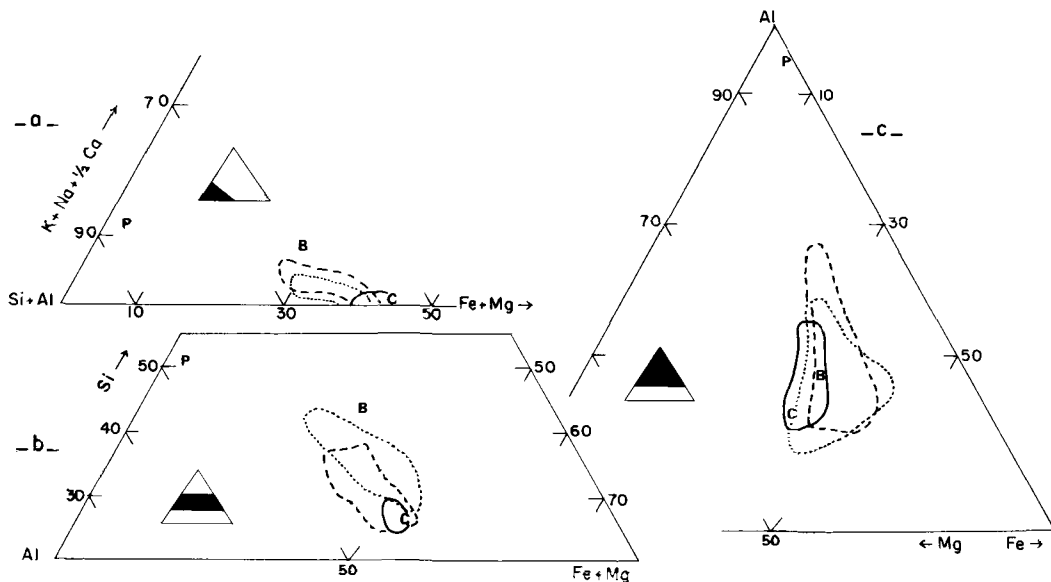


FIG. 5. Mineralogical composition of individual phyllosilicates other than white micas (6-50  $\mu\text{m}$  fractions). Same symbols and conventions as fig. 2.

and Mg seems to decrease as metamorphic grade increases.

**Mineralogical analysis.** The phyllosilicates of this fraction are essentially 10 and 14 Å minerals. Their nature, shown by X-ray diffractometry, varies with the intensity of metamorphism: in the non-metamorphic samples they are illites and mixed-layer chlorite/vermiculites (14C–14V), while in the epimetamorphic samples they are illites and chlorites. The anchimetamorphic samples often contain both chlorite/vermiculite mixed-layers and true chlorite.

Because of their small dimensions, individual crystals have been analysed by STEM. It is not possible to distinguish optically between white micas and chlorites and the results of the analyses are consequently given together on one figure (fig. 6). Although no distinction has been made a priori between 'white micas' and 'chlorites', it is clear that the dispersion fields of the points representative of all the analysed minerals are separated into two zones which roughly correspond to white micas and chlorites. The first striking feature of these three diagrams is that the dispersion area reduces progressively with increase in metamorphism.

The chemical changes from anchizone to epizone are: (i) A reduction of the (Fe + Mg) content in the 'white micas' and diminution of the (K + Na +  $\frac{1}{2}$ Ca) in the 'chlorites' (fig. 6a). (ii) Reduction of the Si content in the 'white micas' as well as in the 'chlorites' (fig. 6b). (iii) Increase of the (Fe + Mg)

content in the 'chlorites' from the diagenetic samples to the anchimetamorphic ones (fig. 6b) and decrease of the Fe/Al ratio from anchi- to epimetamorphic samples with a slight increase of Mg (fig. 6c).

#### The < 2 µm fractions

**Bulk chemical analysis.** Table I allows comparison of the bulk chemical analysis of each of six < 2 µm fractions with its whole-rock analysis. It is seen that: (i) Si and especially Na are less abundant in the < 2 µm fraction than in the whole rock but the difference appears independent of metamorphic grade. (ii) In contrast Al, Fe, Mg, and K are more abundant in the < 2 µm fraction than in the whole rock. Mg and Fe proportional ratios decrease with increase in metamorphic grade. (iii) Ti and Mn have an irregular evolution.

**Mineralogical analysis.** Illite is the most abundant mineral in the clay fraction. Its relative abundance (approximately  $\frac{2}{3}$  of the fraction) does not vary significantly throughout the samples. Regionally its different crystallographic parameters vary, as indicated by the crystallinity index variation. One of the changes involved in this evolution is the progressive loss of expandable (smectite) layers from the initial illite/smectite mixed-layer minerals. In samples from the eastern part of the section (e.g. I24), illites are 'regular' minerals characteristic of a low-grade metamorphism. Chlorite is less common. In the non-metamorphic

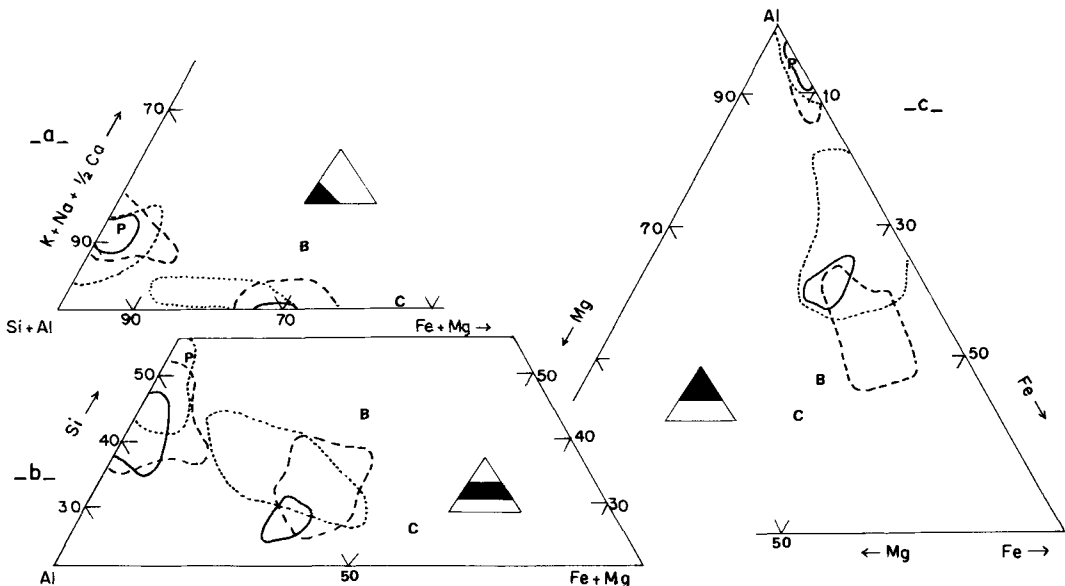


FIG. 6. Mineralogical composition of individual phyllosilicates of the 2–6 µm fractions. Same symbols and conventions as fig. 2.

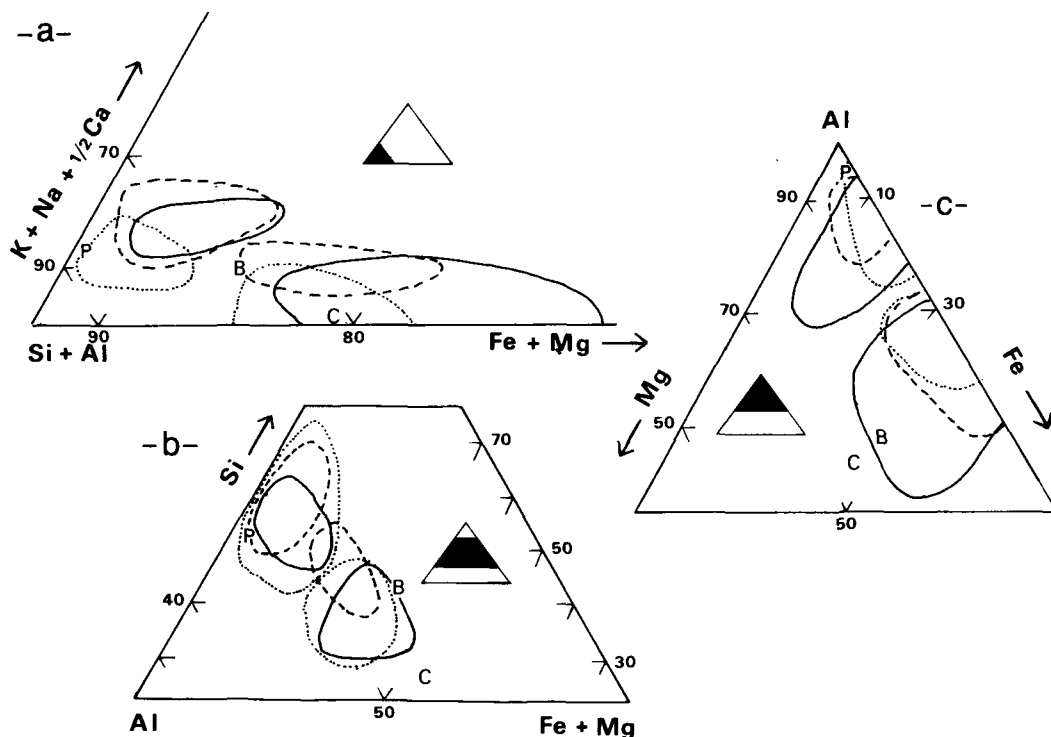


FIG. 7. Mineralogical composition of individual phyllosilicates of the  $< 2 \mu\text{m}$  fractions. Same symbols and conventions as fig. 2.

samples chlorite layers are only present in chlorite/vermiculite mixed-layer minerals but in the anchimetamorphic samples the observed proportion of the vermiculite layers decreases and the  $14 \text{ \AA}$  minerals are true chlorites in the epimetamorphic samples. Finally, in these metamorphic samples, the paragenesis of the  $< 2 \mu\text{m}$  fraction consists of the illite-chlorite association, as already emphasized by Millot (1964).

Microanalyses on particles of the  $< 2 \mu\text{m}$  fraction show there is a higher proportion of inter-layered (mixed-layer) minerals than was supposed and there are relatively few true white micas and chlorites. Most of the particles show some inter-layering. Also, some white micas are K-poor and some particles have intermediate compositions between white mica and chlorite. It is, therefore, sometimes impossible to distinguish the 'illite' and 'chlorite' fields (fig. 7). The fields corresponding to chlorites are probably composed of some true chlorites, but mostly of interlayered mica chlorite. Also, white micas probably include some inter-layered chlorite lamellae. Nevertheless, both 'white micas' and 'chlorites' show an evolution in their composition.

(i) The (Fe + Mg) content in the 'chlorites' increases from the very low grade to the epimetamorphic samples (fig. 7a). K + Na + Ca content increases slightly in the 'white micas' from the diagenetic zone to the anchizone.

(ii) Si seems to decrease slightly in the 'white micas', from diagenetic zone through anchizone to epizone, while the Si content of diagenetic and epizonal 'chlorites' is lower than those from the anchizone (fig. 7b).

(iii) Fe content increases from the diagenetic to the anchimetamorphic samples and Mg increases from the anchimetamorphic to the epimetamorphic samples in the 'chlorites' (fig. 7c).

#### Discussion

In samples representative of various metamorphic conditions the analyses of different size fractions have shown, from one fraction to another and from one sample to another, different mineralogical and chemical variations.

*Optical microscopy.* Possible only in the case of the coarse fraction, it reveals a progressive evolution of the phyllosilicates. This evolution is

especially seen in the brown, detrital biotites, which transform into chlorites with increase in metamorphism.

**X-ray diffractometry.** The progressive disappearance of the mixed-layer minerals and the improvement of illite crystallinity in the finer fractions indicates the development of metamorphic conditions (Weaver, 1960). Purely detrital in the non-metamorphic samples and consisting of a great variety of mineral species, the clay fraction is represented in the anchimetamorphic samples by the illite-chlorite association characteristic of a metamorphic paragenesis (Millot, 1964). In the coarser fractions, a parallel evolution is seen in the progressive regularization of the diffraction peaks which also suggests mineral recrystallizations.

**Bulk analyses.** Comparison of the results from different size fractions (Table I, fig. 8) suggests the following:

(i) In the greywackes studied here, opaques, detrital Na and K feldspars, and quartz with some detrital phyllosilicates compose the coarse fraction that is visible under the optical microscope; the fine fraction, i.e. the matrix, is mostly formed of clay minerals with subordinate quartz and feldspars. Element distribution between different size fractions follows this petrographic disposition. This distribution is here represented by the proportional ratio. It is clear that the predominance of Si, Na, and Ti in the coarse fraction, where their proportional ratio is often higher than 1, results from the preferential location of quartz, detrital feldspar and Ti-rich opaques in this fraction. Conversely, Al, Mg, Fe, Mn, and K are more abundant in the fine-grained fractions because of the concentration of the phyllosilicates in these fractions.

(ii) From the finest to the coarsest fraction, the proportional ratios of each element vary from values  $< 1$  to  $> 1$  depending upon its location in one or another mineral; fig. 8 shows that the value of this ratio is close to 1 for all the elements in the 6–50  $\mu\text{m}$  fraction which has, therefore, the mean composition of the whole rock. It represents a threshold, certainly peculiar to the studied greywackes and determined by their granulometry, between fine clayey fractions and coarse quartzose fractions.

(iii) Comparing non-metamorphic and metamorphic samples (fig. 9), the values of proportional ratios of each element are systematically further from unity in the  $< 2 \mu\text{m}$  fraction for the non-metamorphic samples than for metamorphic ones. In the metamorphic samples, the composition of the  $< 2 \mu\text{m}$  fraction is closer to the whole-rock composition. This suggests that, within each fraction, there are evolutions of the proportional ratios and, thus, element transfers. Fig. 9 shows that from

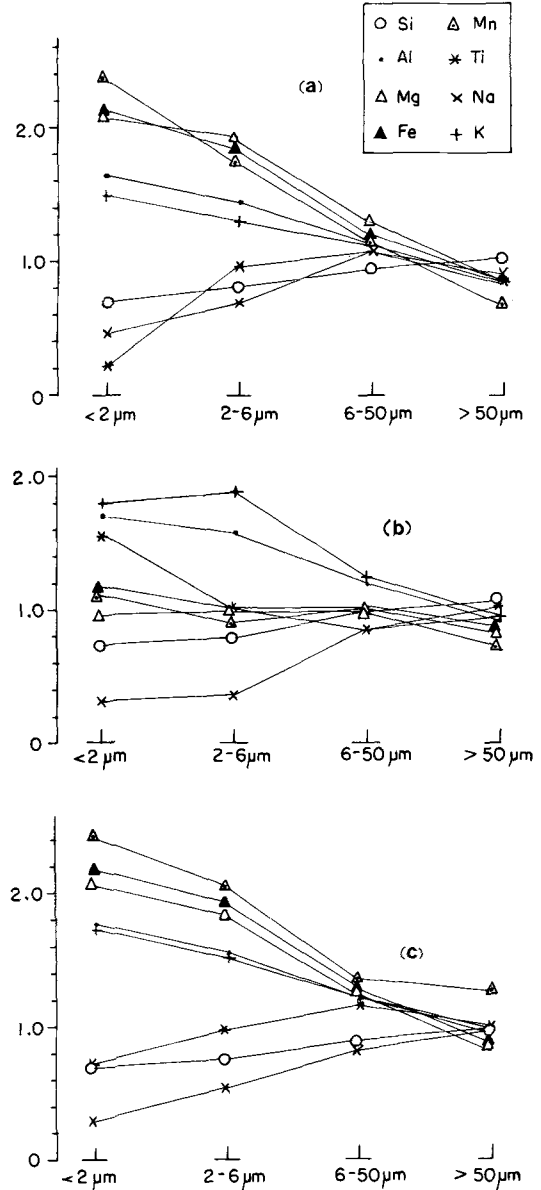


FIG. 8. Proportional ratios (amount of each element in the four size fractions relative to its amount in the whole rock): (a) 78/21 non-metamorphic; (b) I21 epizone; (c) I9 anchizone.

non-metamorphic to metamorphic samples, there is a tendency for Fe, Mg, and Mn to leave the  $< 2 \mu\text{m}$  fraction. This relative diminution of Mg, Fe, and Mn indicates that the relative importance of Fe, Mg, Mn-rich minerals decreases in the  $< 2 \mu\text{m}$  fraction when metamorphism increases. By



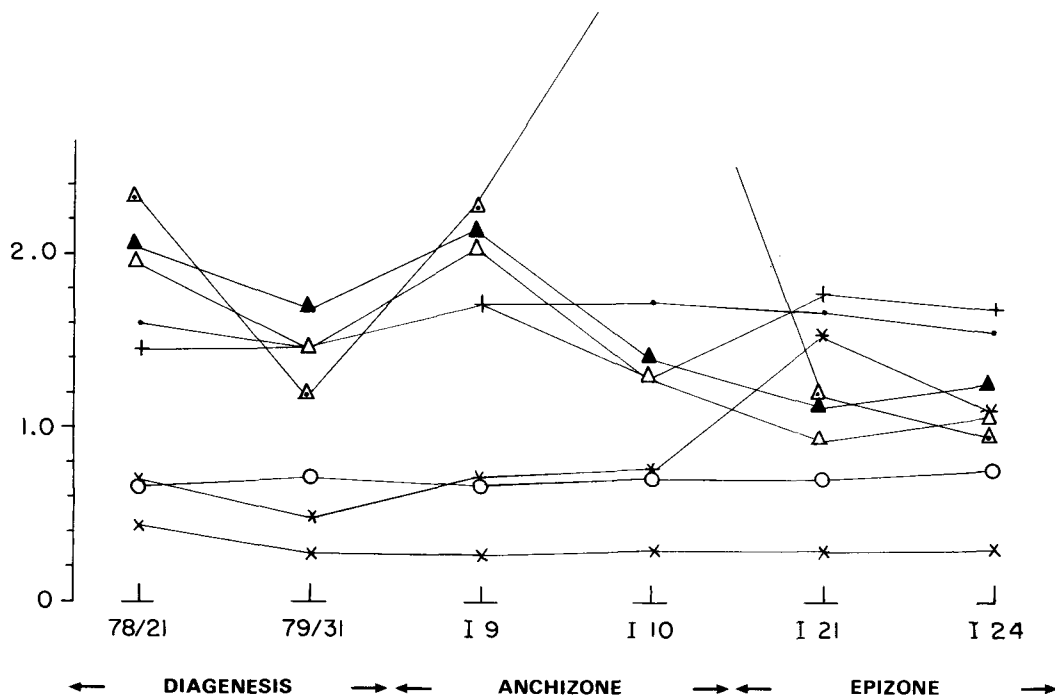


Fig. 9. Evolution of the proportional ratio (see text and fig. 8 for explanation and symbols of the analysed elements) of the  $< 2 \mu\text{m}$  fractions of non-metamorphic to metamorphic samples (see fig. 1 for location of the samples).

comparison, Si and Al remain stable and K seems to increase slightly and irregularly. If we accept, as indicated by X-ray studies, that Fe, Mg, and Mn are neither free nor combined in oxides or hydroxides, but enter the phyllosilicate lattices, their evolution shows that the chlorite content in the phyllosilicates of the  $< 2 \mu\text{m}$  fraction decreases when metamorphism increases. Ti is less abundant than in the whole rock for the non-metamorphic samples and more abundant for the metamorphic samples in the  $< 2 \mu\text{m}$  fraction. This evolution suggests that, during metamorphism, Ti enters the fine fraction and, probably, the phyllosilicate lattices.

There is a corresponding evolution in the coarse fraction. Fig. 10 shows that as metamorphism develops, the variations of the ratios studied above are smaller than in the finer fractions. This suggests reduced mobility of the elements in this fraction during metamorphism. K content, for example, does not decrease as metamorphism increases; the disappearance of the K feldspars is probably accompanied by the growth of white, K-rich micas.

*Individual crystal analyses.* The main conclusions resulting from the analyses of individual crystals (figs. 2-7) are the following:

(i) A general reduction of the dispersion areas

accompanies increasing metamorphism. This indicates a progressive homogenization of the chemical compositions of the crystals in each fraction as metamorphism increases. This homogenization progressively realizes the step between a detrital mineral association, composed of a wide variety of minerals which are not in equilibrium together, to a metamorphic paragenesis, where a restricted number of mineral phases are stable. In the low-grade metamorphism attained here, this paragenesis is the white mica-chlorite assemblage.

(ii) While the dispersion areas diminish, the centre moves. This is particularly clear on several diagrams (e.g. fig. 3a). This evolution indicates, in each fraction, a displacement of the mean chemical composition of the analysed minerals, i.e. white micas and chlorites, during metamorphism: white micas evolve generally (except perhaps the  $< 2 \mu\text{m}$  'illites') toward Al-rich compositions at the expense of Si and (Fe + Mg). However, this evolution is not achieved during the low-grade metamorphism, where most of the white micas are still phengites and not Al-muscovites. The evolution of chlorite is often greater than that of white mica, especially in coarse fractions (fig. 3); during increasing metamorphism, chlorites commonly lose Si and

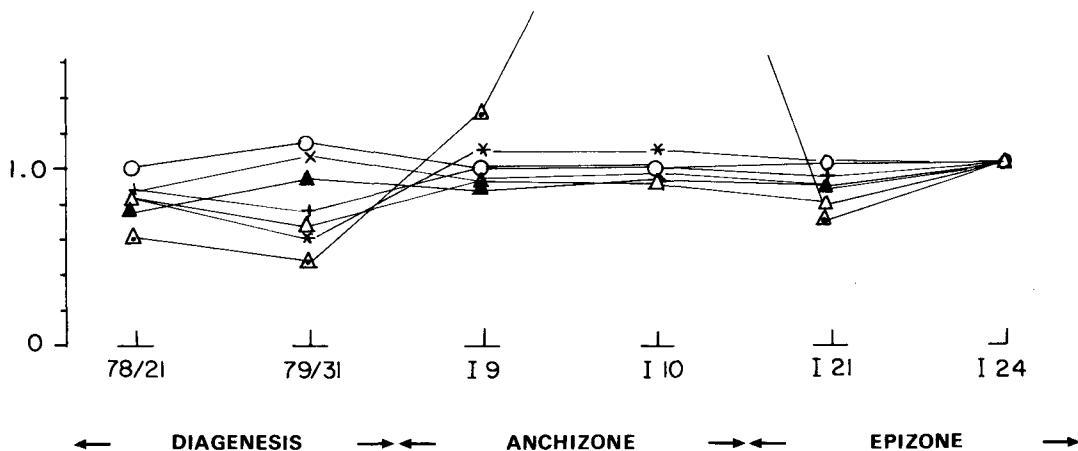


FIG. 10. Evolution of the proportional ratio (see text and fig. 8 for explanation) of the analysed elements from the  $> 50 \mu\text{m}$  fractions of non-metamorphic to metamorphic samples (see fig. 1 for location of the samples).

Al and they become richer in (Fe + Mg). At the end of this evolution, in all fractions of the most metamorphic samples, they become Mg-chlorites.

(iii) The present study does not show any significant size-fraction control in these mineral evolutions. It is provisionally concluded that the mineralogical and chemical reorganization which accompanies metamorphism occurs simultaneously in all the size-fractions and that no important delay exists between recrystallizations in coarse and fine fractions.

In conclusion, in a series of samples of similar lithology, this study indicates some mechanisms which act during the onset of metamorphism and its development. As well as crystallographic changes, which are not studied here, these mechanisms are chemical transfers, as demonstrated by chemical changes in bulk analyses as well as in individual crystal analyses.

Chemical transfers between different fractions reorganize the mineralogical composition of the fractions. Owing to the important mobility of Mn, Fe, Mg, and Ti during increasing metamorphism, the fine-grained fractions lose a part of their chlorite content and they become white mica-rich. Conversely, as indicated by optical microscopy observations, the coarse fractions become more chloritic and lose their Ti-rich opaques and detrital K-feldspars. In other words, during the onset of metamorphism and its development, phyllosilicates of the fine fraction evolve mostly toward white micas whereas those present in the coarse fraction evolve toward chlorites.

Concurrently with these transfers between different fractions, increasing metamorphism induces

in all size fractions a progressive reduction of the variations between mineralogical and chemical compositions of the detrital minerals. This reduction leads to the homogenization of these compositions while minerals recrystallize. The result of this homogenization is the metamorphic white mica-chlorite paragenesis.

*Acknowledgements.* Thanks are due to our colleague Dr H. Paquet for a critical reading of an early draft of this paper. Useful comments of an anonymous reviewer and those of Dr D. Robinson are also gratefully acknowledged.

## REFERENCES

- Dunoyer de Segonzac, G. (1969) *Mém. Serv. Carte Géol. Als. Lorr.* **29**, 1–320.
- Duplay, J. (1982) Thèse 3e cycle, Univ. Poitiers.
- Frey, M. (1970) *Sedimentology*, **15**, 261–79.
- (1978) *J. Petrol.* **19**, 93–135.
- Kisch, H. J. (1980) *J. Geol. Soc. London*, **137**, 271–88.
- Kubler, B. (1964) *Rev. Inst. fr. Petrol.* **19**, 1093–113.
- (1966) In *Colloque sur les étages tectoniques*. La Baconnière, Neuchâtel, Switzerland, 105–22.
- (1968) *Bull. Centre Rech. Pau S.N.P.A.* **2**, 385–97.
- Liewig, N. (1981) Thèse 3e cycle, Univ. of Strasbourg.
- McDowell, S. D., and Elders, W. A. (1980) *Contrib. Mineral. Petrol.* **74**, 293–310.
- Millot, G. (1964) *Géologie des argiles*, Masson et Cie, Paris, 499 pp.
- Nicot, E. (1981) *Bull. Minéral.* **104**, 615–24.
- Parker, A., Allen, J., and Williams, B. (1983) *J. Geol. Soc. London*, **140**, 769–79.
- Piqué, A. (1979) *Sci. Géol., Mém.* **56**, 1–243.
- Jeannette, D., and Michard, A. (1980) *J. Struct. Géol.* **2**, 55–61.

- Teichmüller, M., Teichmüller, R., and Weber, K. (1979) *Fortschr. Geol. Rheinh. u. Westf.* **27**, 201-76.
- Velde, B. (1967) *Contrib. Mineral. Petrol.* **14**, 250-8.
- Weaver, C. E. (1960) *Bull. Am. Assoc. Petrol. Geol.* **44**, 1505-18.
- Weber, K. (1972) *Neues Jahrb. Geol. Paläont. Abh.* **141**, 333-63.
- Winkler, H. (1976) *Petrogenesis of metamorphic rocks.* Springer-Verlag, New York.
- Wybrecht, E. (1984) Thèse de 3e cycle. Univ. of Strasbourg.
- Piqué, A., and Weber, F. (1983) EUG Meeting, Strasbourg, abstr.

[Manuscript received 14 April 1984;  
revised 14 August 1984]