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# Sedimentology, clay mineralogy and depositional environment of Purbeckian green marls (Swiss and French Jura)

By JEAN-FRANÇOIS DECONINCK and ANDRÉ STRASSER<sup>1)</sup>

## ABSTRACT

Purbeckian green marls in the Swiss and French Jura usually occur at the top of small-scale shallowing-upward sequences which commonly end with evidence of subaerial exposure.

Clay-mineralogical assemblages are mainly composed of illite and detrital Al-Fe-smectite in the northwestern part of the study area, and almost entirely of authigenic illite in the southeast. This geographical distribution originates a) from detrital input caused by erosion of smectite-rich soils which developed in downstream continental areas under hot and seasonally humid climates, b) from transitions of Al-Fe-smectite to Fe-illite determined by cyclic wetting by marine waters and drying. These results are in agreement with mixed marine and freshwater fossils found in the green marls, and with their sedimentological context.

## RÉSUMÉ

Les marnes vertes purbeckiennes du Jura suisse et français se situent généralement au sommet de séquences émerives et sont probablement restées émergées durant une longue période.

Leur fraction argileuse, étudiée sur une centaine d'échantillons répartis sur 24 coupes, est constituée d'un mélange d'illite et de smectite alumino-ferrique dans les chaînons nord-occidentaux du Jura. En revanche, dans les secteurs sud-orientaux, les illites ferrifères dominent largement le cortège argileux. Cette répartition géographique a pour origine a) un apport détritique faible déterminé par l'érosion de sols riches en smectite et développés sur les zones continentales peu déclives, sous climats chauds à forts contrastes saisonniers de l'humidité, b) des transformations de smectites alumino-ferriques en illites ferrifères par l'intermédiaire d'interstratifiés irréguliers illite-smectite. Ces transformations résultent d'alternances de périodes durant lesquelles les smectites étaient en contact avec l'eau de mer et de périodes d'assèchement déterminées par le climat chaud.

Les marnes vertes riches en illite ferrifère sont les témoins d'émersions partielles à proximité du milieu marin et peuvent par conséquent être utiles aux reconstitutions paléogéographiques. Il s'agit typiquement de sédiments ayant subi à la fois des influences continentales et marines, ce qui est en accord avec les données faunistiques et le contexte sédimentologique.

## 1. Introduction

### *Stratigraphic and regional setting*

Purbeckian carbonate sediments and marls in the Swiss and French Jura Mountains are characterized by shallow-marine, brackish, lacustrine and hypersaline facies. They have been deposited in the subtidal, intertidal and supratidal zones of a wide carbonate shelf on the northern margin of the Tethys ocean.

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The Purbeckian series (20–40 m) is placed between the Portlandian “Tidalites de Vouglans” (BERNIER 1984) and the Middle-Berriasian Pierre-Châtel Formation (STEINHAUSER & LOMBARD 1969). It has been dated by ammonites (CLAVEL et al. 1986), by charophytes and ostracods (MOJON & STRASSER 1987), and by sequence stratigraphy (STRASSER, in press) to be of Lower Berriasian age. The Swiss and French Purbeckian thus correlates with parts of the Lulworth Beds in England (WIMBLEDON & HUNT 1983, NORRIS 1985), and with parts of the Münders Formation in Germany (DÖRHÖFER & NORRIS 1977).

Outcrop limits of the Purbeckian in the Jura and the sampled sections are indicated in Figure 1. Due to the relative abundance of marly layers (especially in the north and northwest of the study area) the Purbeckian outcrops are poor and geomorphologically expressed as meadow-covered valleys (the “combe purbeckienne” of French-speaking cartographers). Consequently, many of the studied sections are incomplete. The marls frequently display a greenish color (“marnes vertes”).

### *History of research*

Many authors working in the Jura Mountains mentioned the presence of freshwater fossils in the marly layers of the Purbeckian (e.g., CHOFFAT 1877, MAILLARD 1884, JOUKOWSKY & FAVRE 1913, FAVRE & RICHARD 1927). DONZE (1958) found mixed marine and lacustrine faunas in the green marls and considered them to be transitional between marine and freshwater deposits. Gypsum and dolomite-bearing marls have been described from the lower part of the Purbeckian, especially in the northern part of the study area (LORIOU & JACCARD 1865, MAILLARD 1884, CAROZZI 1948, DONZE 1958). HÄFELI (1966) was the first to analyze the clay fraction of Purbeckian sediments. He found illite and partly authigenic montmorillonite in lacustrine and brackish-water deposits. A detailed analysis of clays at the Jurassic–Cretaceous boundary has been carried out by PERSOZ & REMANE in 1976. The association of green marls with black pebbles, which indicate terrestrial exposure, has been described by STRASSER & DAVAUD (1983).

Green marls associated with shallow-marine and peritidal facies occur also in other areas and in other geological epochs. WRIGHT (1986) describes green clays composed of illite and smectite in the Carboniferous of South Wales. They are associated with intertidal to supratidal laminites, and with caliche crusts. In the Triassic lead-zinc deposits of Bleiberg–Kreuth (Austria) green marls are found together with intertidal and supratidal facies, as well as with black pebbles (EPPENSTEINER 1965, BECHSTÄDT 1979, BECHSTÄDT & DÖHLER-HIRNER 1983). The clays consist mainly of illite. The late Triassic Dachstein Formation of Austria contains green and red marls as matrix of intertidal conglomerates, and as infillings of cavities in the underlying sediment (FISCHER 1964, PILLER 1976). The green marly layers occur in a cyclic pattern. They are interpreted as residual sediment which formed during cyclic emersions of a shallow carbonate platform (FISCHER 1964, PILLER 1976, BECHSTÄDT 1979). KOSTELKA & SIEGL (1966) and SCHNEIDER et al. (1977) interpreted the green marls of Bleiberg–Kreuth as tuffites but, as BECHSTÄDT (1979) pointed out, there is no reason why volcanic sediments should show a preference for intertidal to supratidal conditions.

Jurassic green marls and black pebbles in a supratidal context have been described by SEYFRIED (1980) from Spain. Late-Jurassic to early-Cretaceous green marls containing

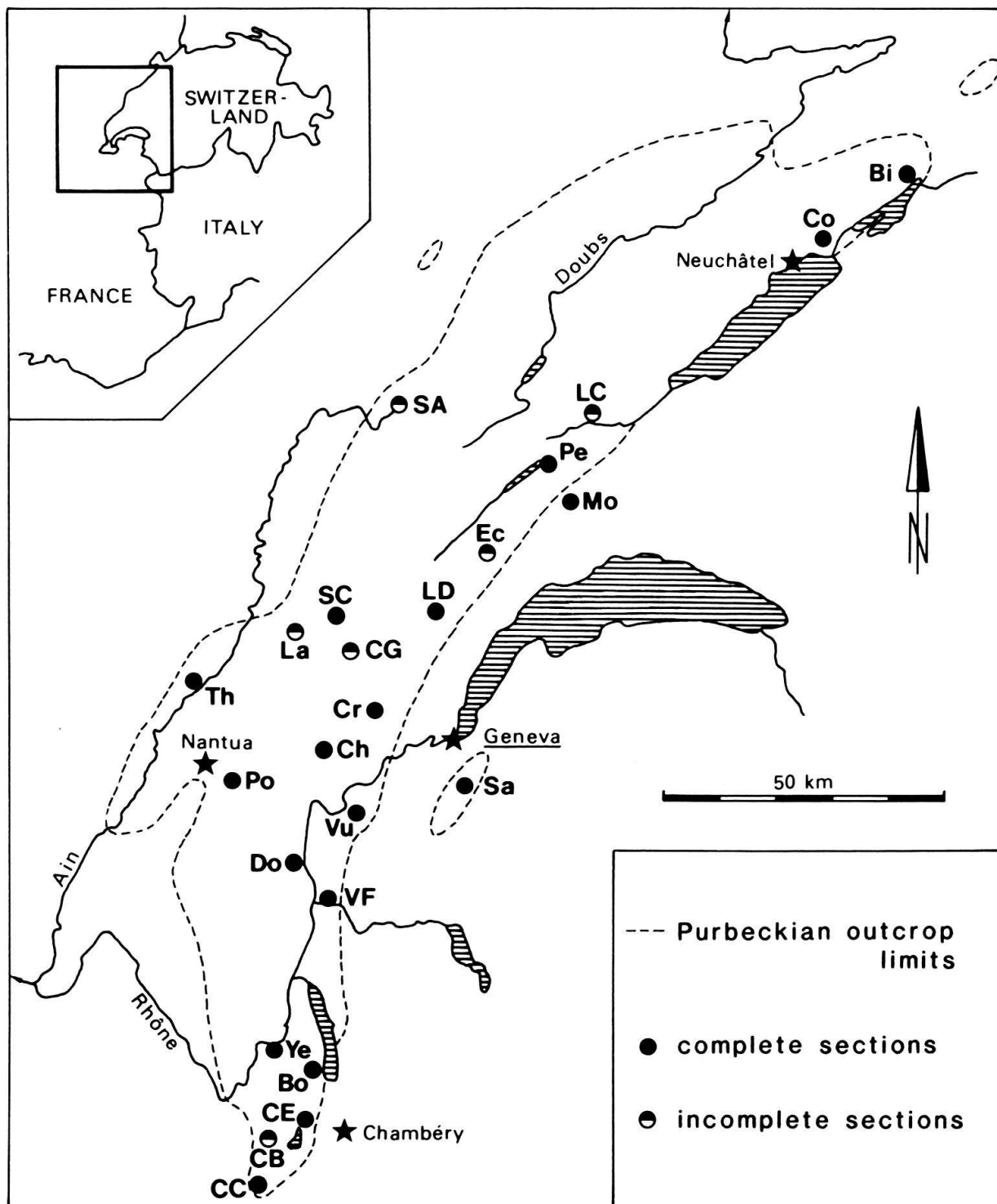


Fig. 1. Location map. Bi: Bienne, Bo: Bourdeaux, CB: Col du Banchet, CC: Cluse de Chailles, CE: Col de l'Epine, CG: Chapeau du Gendarme, Ch: Chézery, Co: Cornaux, Cr: Crozet, Do: Dorche, Ec: Echadex, La: Lavans, LC: Les Clées, LD: La Dôle, Mo: Morand (cored section), Pe: Pétrafélix, Po: Poizat, Sa: Salève, SA: Source de l'Ain, SC: Saint-Claude, Th: Thoirrette, VF: Val du Fier, Vu: Vuache, Ye: Yenne.

mainly illite and mixed-layer minerals are found interstratified with shallow-marine to supratidal limestones in Provence, France (BABINOT et al. 1971, COTILLON 1971, 1974). They are related to discontinuity surfaces which appear in a cyclic pattern.

In this paper we would like to contribute to a more detailed interpretation of the clay mineralogy and the depositional setting of Purbeckian marls.

## 2. Sedimentological context

### *Sequential position of green marls*

Purbeckian sediments in the Jura are composed of small shallowing-upward sequences. These either consist of several beds of successively subtidal, intertidal, and supratidal facies, or they are reduced to one bed with superimposed intertidal or supratidal features. The thickness of a single sequence varies between 20 cm and 1.50 m. The base frequently contains reworked elements of the underlying deposits. These small-scale sequences are thought to have been caused by precession cycles of the equinoxes inducing cyclic climatic changes which in their turn caused sea-level fluctuations and/or changes in carbonate productivity (STRASSER, in press). As water depth and subsidence rates were often too low to accommodate the sediment input, most sequences are incomplete, reworked, or partly eroded. Similar shallowing-upward sequences ("punctuated aggradational cycles") have been described by GOODWIN & ANDERSON (1985).

The marly layers are regularly found at the top of the sequences (Fig. 2). They may reach 1.40 m in thickness and contain lenses and nodules of limestone, or they are reduced to a mm-thin film between two limestone beds. They may evolve out of laminated algal micrites or pelmicrites with birdseyes indicating tidal-flat environments, or they overlie with a sharp contact subtidal lagoonal sediments. The contact often is erosional, and more or less rounded pebbles of the underlying facies are incorporated in the marls. Black-pebble conglomerates are common and locally overlie caliche crusts (STRASSER & DAVAUD 1982). Pedogenic overprinting of the underlying bed (indicated by circumgranular cracking, alveolar texture and root traces; ESTEBAN & KLAPPA 1983) caused fracturing and dissolution voids which are filled by marls. Fissures between blocks of beachrock contain conglomerates with a marly matrix.

The sedimentological context of the Purbeckian marls is consistent with most interpretations cited in the literature above. GOODWIN & ANDERSON (1985) and STRASSER (in press) propose a time-span of about 20,000 years for a single sequence. As the sedimentation of, e.g., ooid sand bars or tempestites can be very rapid, a lot of time is represented by exposure surfaces and beds with reworked material. This suggests that the marls commonly found at the top of the sequences must have been subaerially exposed for a considerable length of time.

### *Facies of marls*

The marls of the studied Purbeckian sections normally contain between 30 and 80%  $\text{CaCO}_3$ . In a hypersaline context dolomite may reach 50%, celestite 7%. Gypsum occurs only as calcitic pseudomorphs in the sampled sections. Detrital quartz is virtually absent, and automorphic, authigenic quartz never exceeds 10%. Only in rare cases do the samples consist exclusively of clay minerals. The typical color of Purbeckian marls is

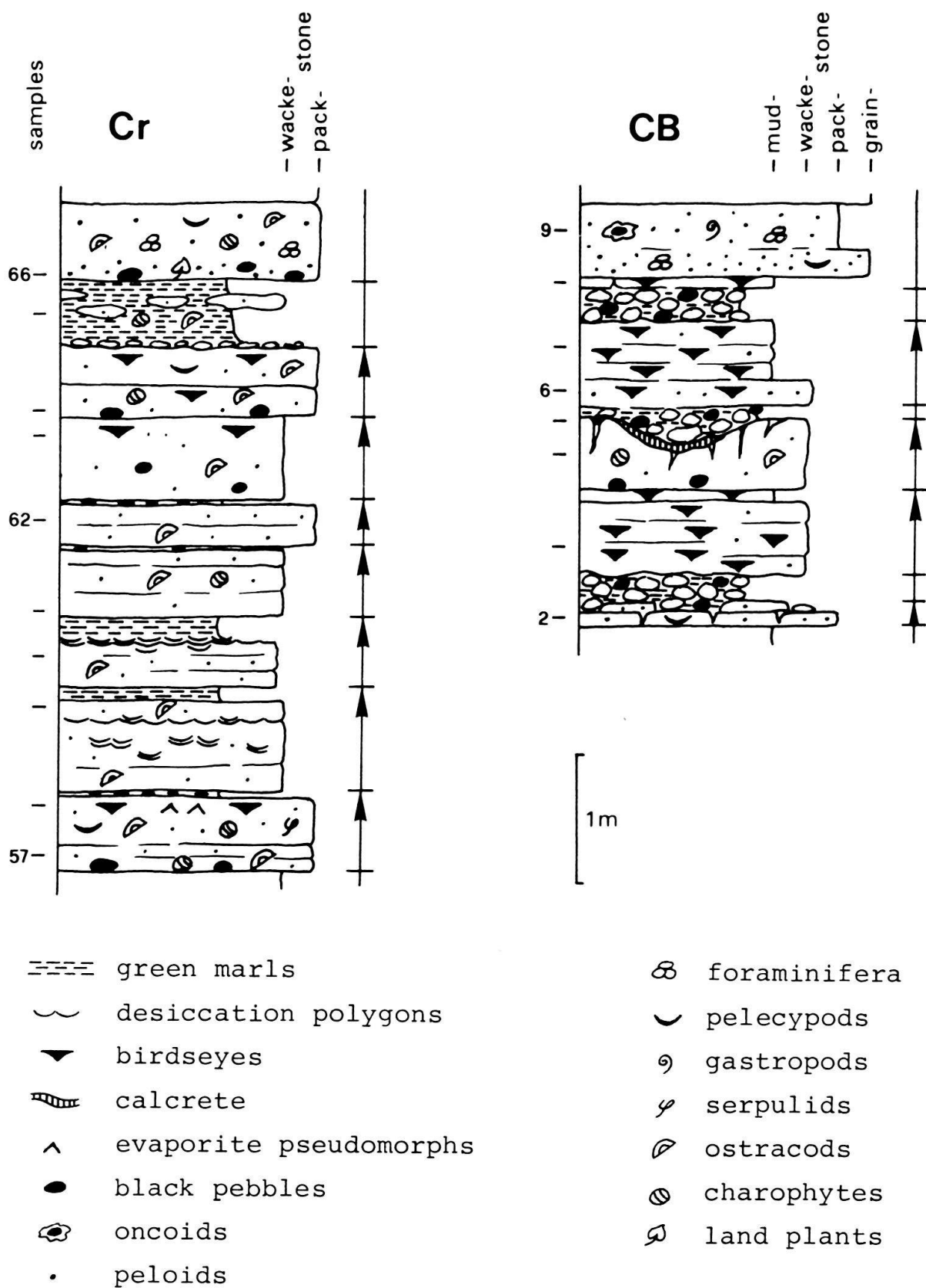
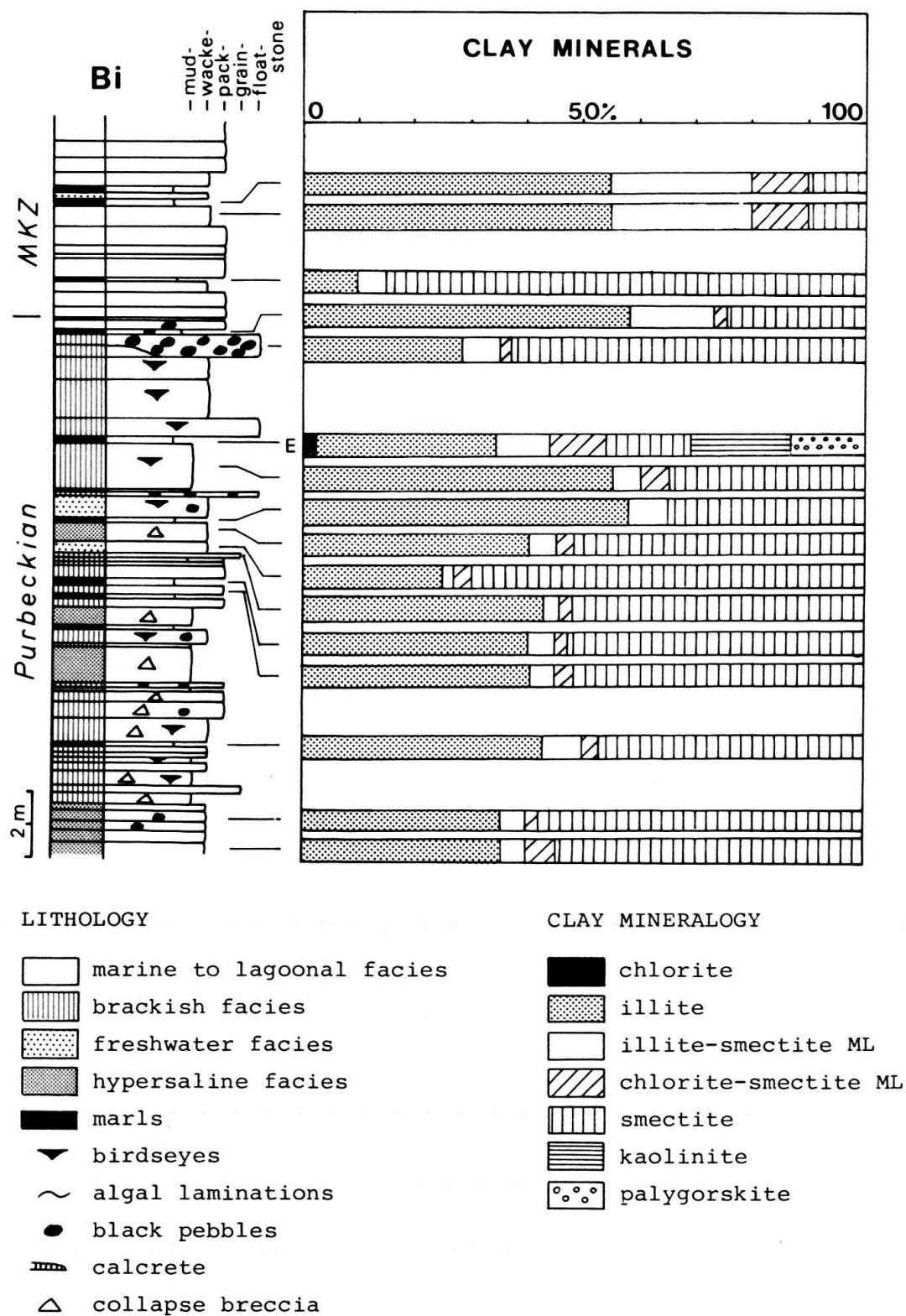


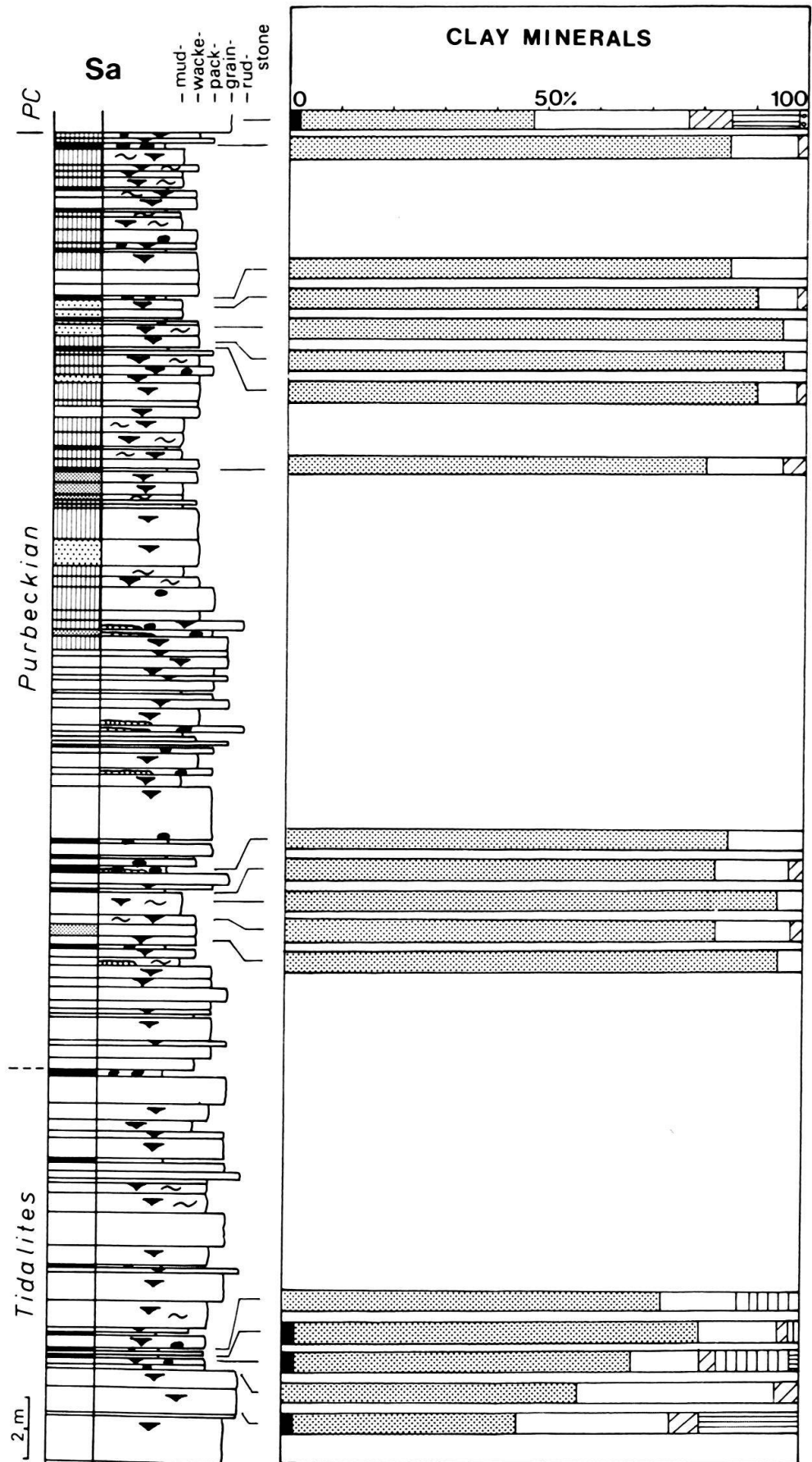
Fig. 2. Sequential position of Purbeckian green marls (examples from Crozet and Col du Banchet sections). Arrows indicate small-scale shallowing-upward sequences.



PC : formation of "Pierre-Châtel"

MKZ: "Mergel-und-Kalk-Zone" (HÄFELI 1966), corresponding to PC

Fig. 3. Lithology and clay mineralogy of Salève (Sa) and Bienne (Bi) sections. Salève: note the relatively homogeneous clay assemblages and the absence of kaolinite in the Purbeckian. Bienne: note detrital event E, marked by a heterogeneous clay assemblage.



greenish-grey (yellow or reddish-grey when oxidized). Dark brown marls are found where organic matter is present (TOC 0.1–0.3%).

Microfauna and microflora found in the marls do not necessarily have the underlying facies. Rich assemblages of charophytes as well as freshwater ostracods and gastropods sometimes follow lacustrine limestones, but frequently the organisms have a mixed origin. Freshwater and brackish fossils occur together with foraminifera, pelecypods and serpulids of more or less restricted marine environments, which may well be explained by reworking of the sediment by waves and storms. Charophytes are locally associated with evaporites (MOJON & STRASSER 1987). This implies either reworking, or seasonal changes of salinity. A climate with hot and dry summers and rainy winters has been suggested by FRANCIS (1984) for the Purbeck of England. Bone fragments and teeth of fishes and saurians occur sporadically in the marls (P. O. Mojon, pers. comm.). Pieces of wood, as well as abundant black pebbles point to nearby vegetated lands (STRASSER 1984).

### 3. Clay mineralogy

#### *Material and analytical methods*

Clay mineralogical analyses have been carried out on 125 samples from 24 sections (Fig. 1). The samples consist essentially of marls but the clay fraction ( $< 2 \mu\text{m}$ ) of some limestones has also been studied. Moreover, some samples from the Portlandian and from the overlying Formation of Pierre-Châtel have been included.

X-ray diffraction (XRD) analyses were carried out using a Philips diffractometer with  $\text{CuK}_\alpha$  radiation. The clay fraction ( $< 2 \mu\text{m}$ ) was separated by sedimentation and oriented samples were prepared using the method described in detail by HOLTZAPFFEL (1985). The oriented pastes were air-dried, then saturated with ethylene-glycol, and heated at  $490^\circ\text{C}$  during 2 hours. Average proportions of clay minerals are estimated measuring the height and the surface of the diffraction peaks. The error margin is about 5% (HOLTZAPFFEL 1985). The (060) reflection was measured on powder specimen packed into cavity holders. DTA analyses have been performed on 8 samples, and chemical analyses (both atomic absorption and microprobe) have been done on twelve monomineralic clay fractions. Furthermore, clays have been observed by transmission electron microscopy (TEM).

#### *Results*

Clay mineral assemblages of the Purbeckian are mainly composed of illite, smectite, and irregular illite-smectite mixed-layers (10–14s). Chlorite, kaolinite, irregular chlorite-smectite mixed-layers (14c–14s) and palygorskite generally appear in very small quantities. These results agree with those published by PERSOZ & REMANE (1976).

The clay mineralogy is plotted for the sections of Bienne and Salève which have been sampled in detail (Fig. 3). The main two types of X-ray diffraction patterns are given in Figure 4. In the “Tidalites de Vouglans” and in the Pierre-Châtel Formation, kaolinite is usually present, and values range up to 15–20%. This difference to the Purbeckian facies allows a good distinction between the formations.

#### *Illite*

In many samples of Purbeckian facies (marls as well as limestones) the clay fraction contains up to 90–100% illite. Illite is generally of poor crystallinity ( $0.6^\circ 2\theta$  to  $1^\circ 2\theta$ ) and shows a low ratio of the reflections 002/001 (illite crystallinity index corresponds to width of the (001) peak at half peak height; KÜBLER 1966). The latter observation suggests a

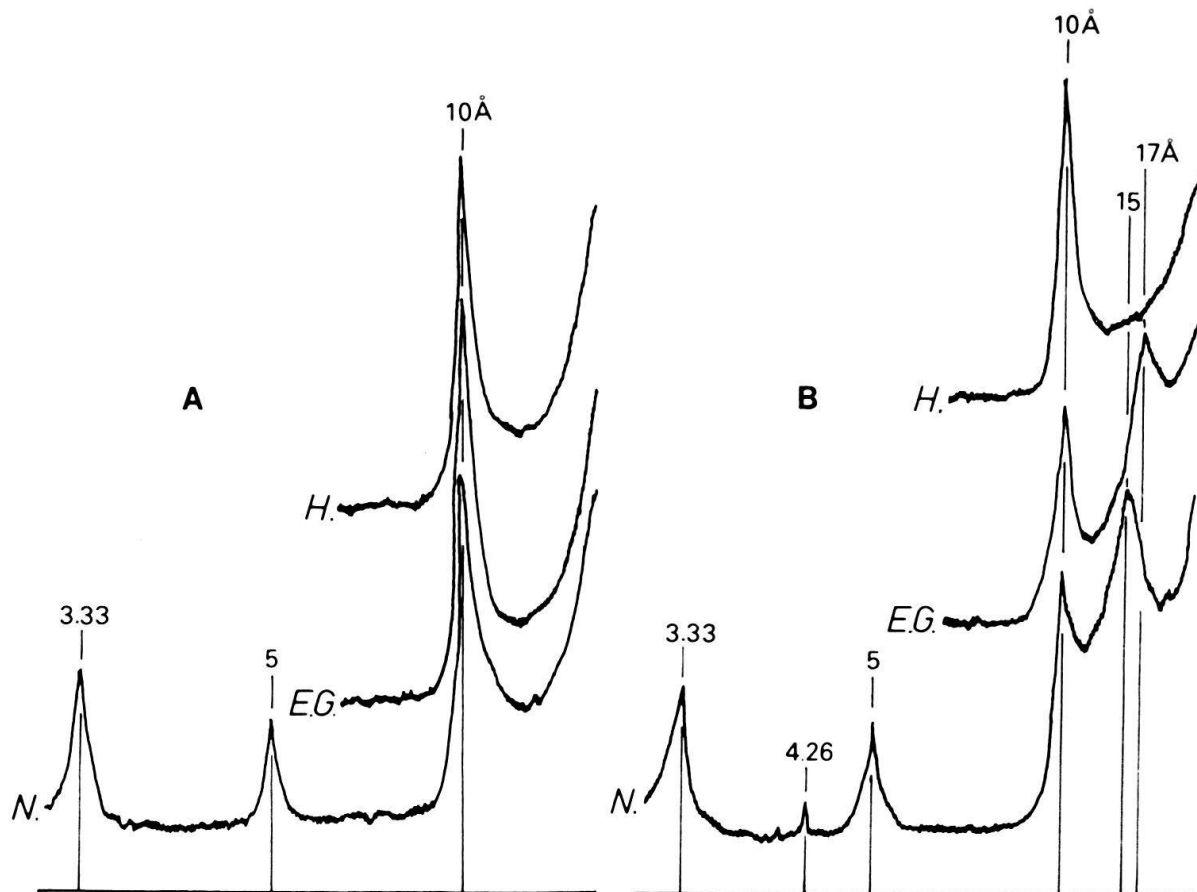


Fig. 4. X-Ray diffraction patterns of both types of Purbeckian clay-mineral assemblages.

A: almost pure illite. B: mixture of illite, smectite and illite-smectite mixed-layers.

(N: natural, air-dried; E.G: ethylene-glycol; H: heated)

relatively high Fe content of the octahedral layer (BRINDLEY & BROWN 1980). The XRD pattern of the powder specimen shows a (060) reflection at  $1.500\text{\AA}$  and points to a dioctahedral character. Chemical analyses of pure illite, both by atomic absorption and microprobe, and the deduced structural formulas confirm the observations made from XRD patterns (Table 1).

Table 1: *Example of chemical composition and structural formulas of Purbeckian illite.*

|            | SiO <sub>2</sub>                                                                                                                                                                              | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | CaO  | MgO  | Na <sub>2</sub> O | K <sub>2</sub> O | TiO <sub>2</sub> |
|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|--------------------------------|------|------|-------------------|------------------|------------------|
| Atomic     | 52,90                                                                                                                                                                                         | 21,81                          | 7,35                           | 1,30 | 3,56 | 0,18              | 5,36             | 0,65             |
| Absorption | $(\text{Si}_{3,55}, \text{Al}_{0,45})(\text{Al}_{1,28}, \text{Fe}_{0,37}, \text{Mg}_{0,36}, \text{Ti}_{0,03}) \text{K}_{0,46}, \text{Ca}_{0,09}, \text{Na}_{0,02} \text{O}_{10}(\text{OH})_2$ |                                |                                |      |      |                   |                  |                  |
| Microprobe | 52,41                                                                                                                                                                                         | 20,81                          | 7,45                           | 0,63 | 3,93 | 0,13              | 6,36             | 0,32             |
|            | $(\text{Si}_{3,58}, \text{Al}_{0,42})(\text{Al}_{1,25}, \text{Mg}_{0,40}, \text{Fe}_{0,38}, \text{Ti}_{0,02}) \text{K}_{0,53}, \text{Ca}_{0,05}, \text{Na}_{0,02} \text{O}_{10}(\text{OH})_2$ |                                |                                |      |      |                   |                  |                  |

From these formulas, we can plot the Purbeckian illite on the diagram used by JUNG (1954), GABIS (1963) and PORRENGA (1968) (Fig. 5). The graph shows that Purbeckian illite has a chemical composition intermediate between illite and glauconite.

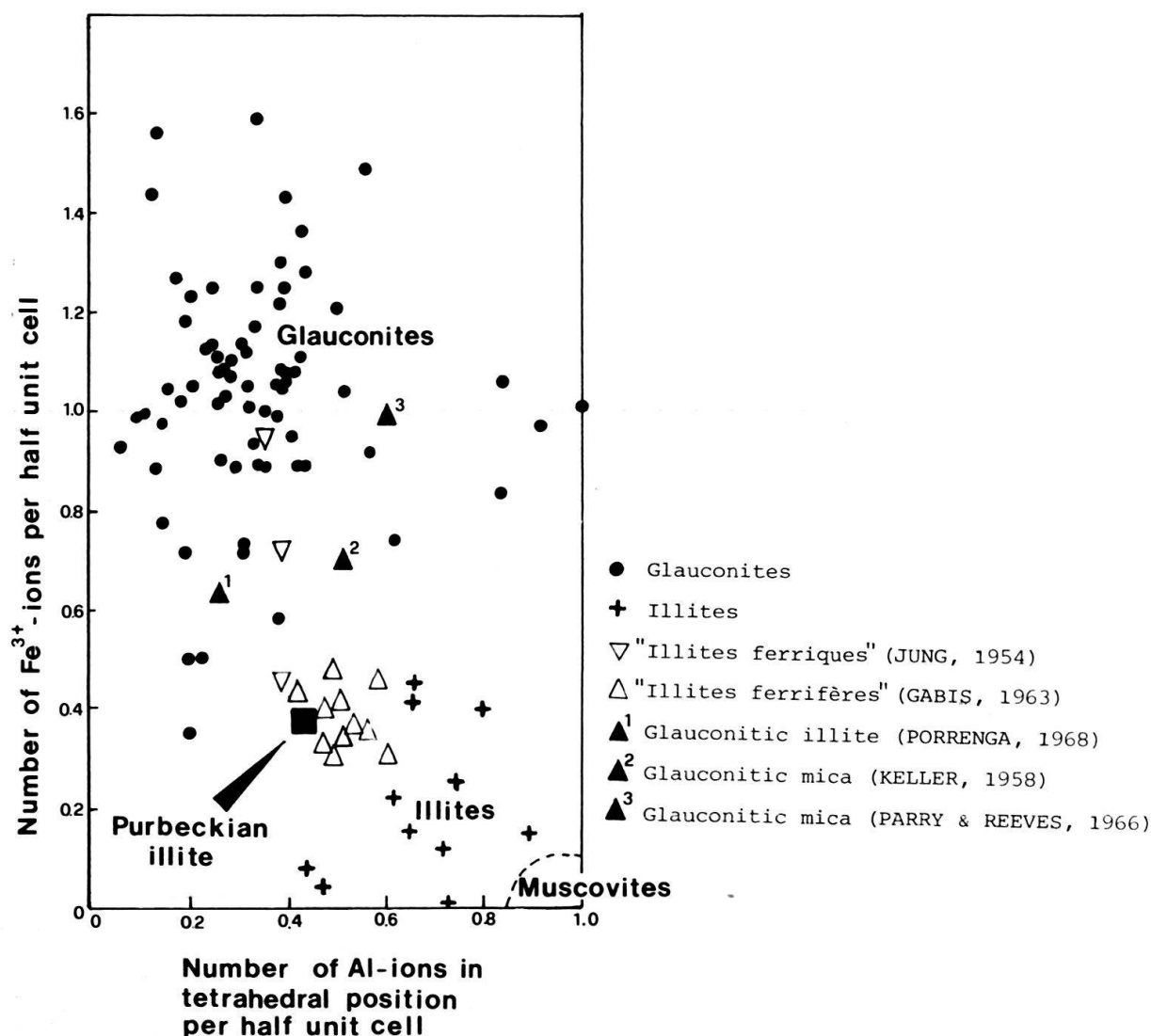


Fig. 5. Graph showing Purbeckian Fe-rich illite with a chemical composition intermediate between illite-muscovite and glauconite (from PORRENGA 1968).

The DTA curve (Fig. 6A) is characteristic of illite. It shows an endothermic peak around  $120^{\circ}\text{C}$  which corresponds to the dehydration accompanied by a loss of mass of 7%. It equally shows an endothermic peak at  $530^{\circ}\text{C}$  which reflects dehydroxylation. Loss of mass is 4,8%. Finally, one can observe an endothermic effect (destruction of the lattice) immediately followed by an exothermic effect around  $930^{\circ}\text{C}$  (recrystallization). This DTA curve is very similar to curves of Oligocene illite from the Velay area (France) studied by GABIS (1963).

TEM observations indicate that illite particles are of very small sizes and have fleecy shapes (Fig. 7A, B, C). This aspect is unusual for detrital micas which generally display sharp limits. Illite particles are almost undistinguishable from smectites.

### Smectite

Detailed studies of smectite are difficult, as this mineral is always associated with illite and mixed-layers. However, DTA analyses have been performed on smectite-rich clay

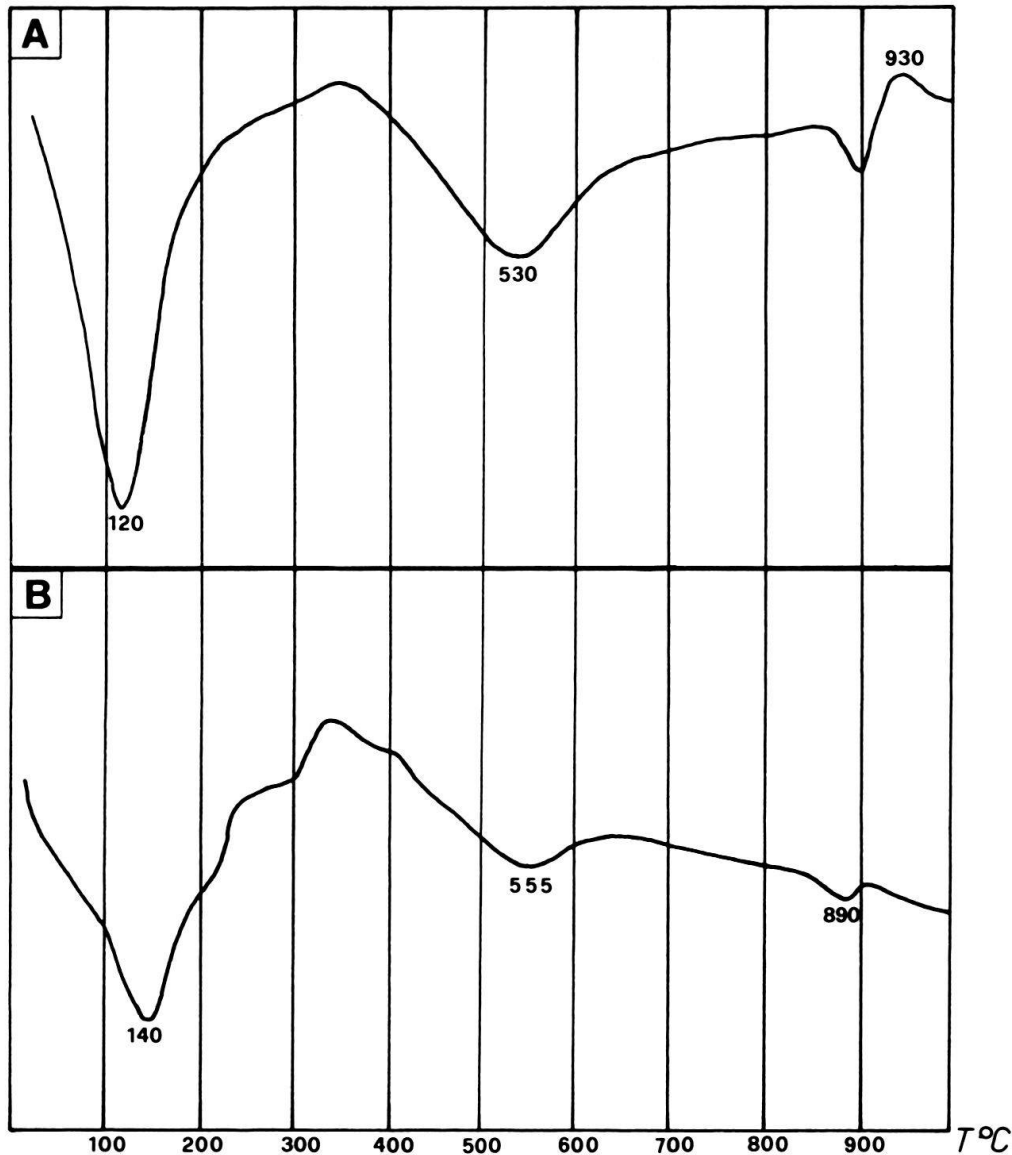
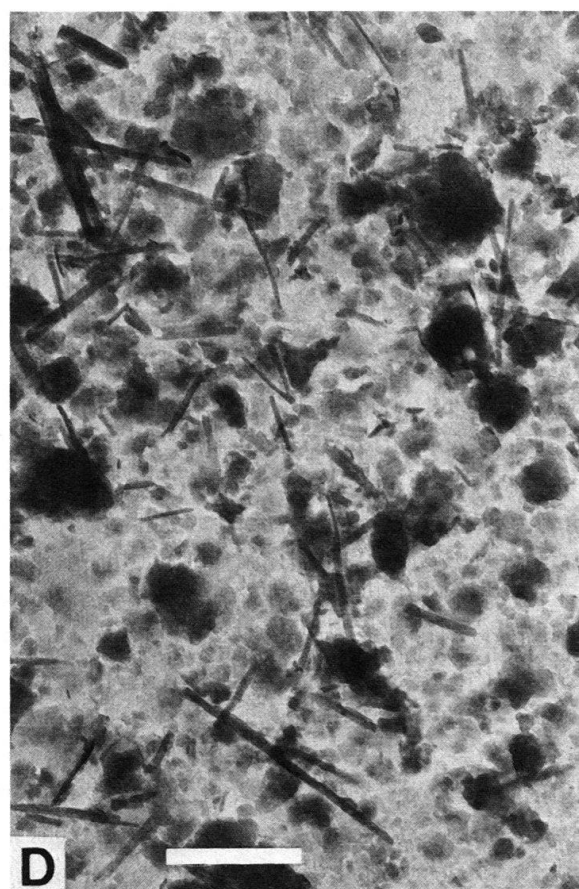
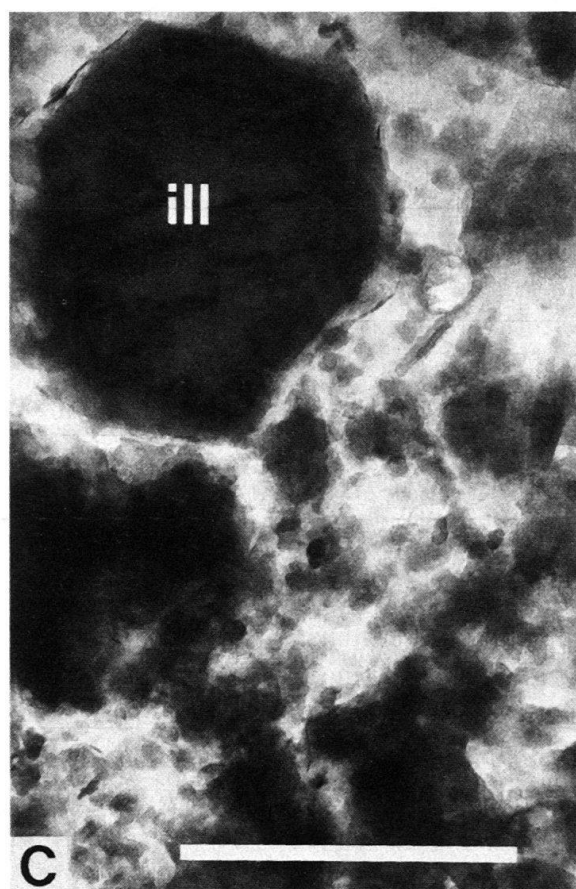
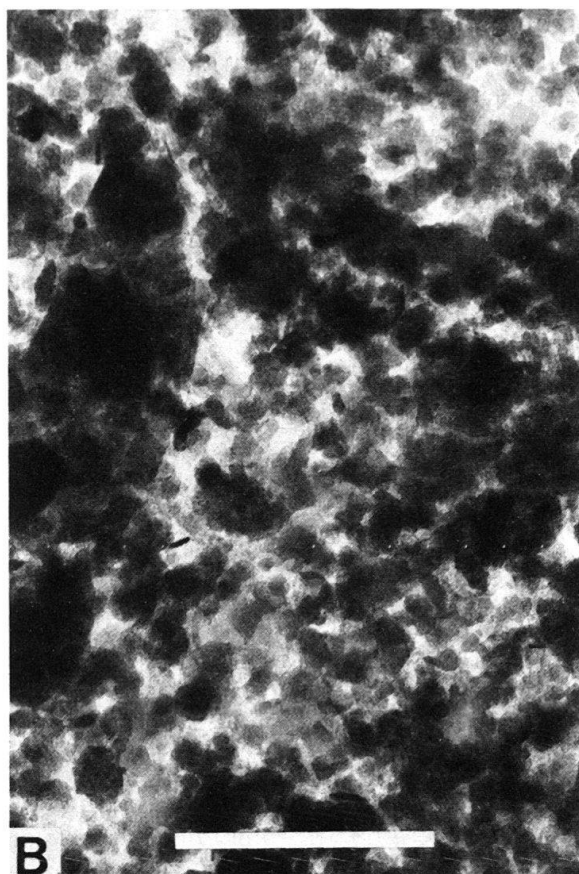
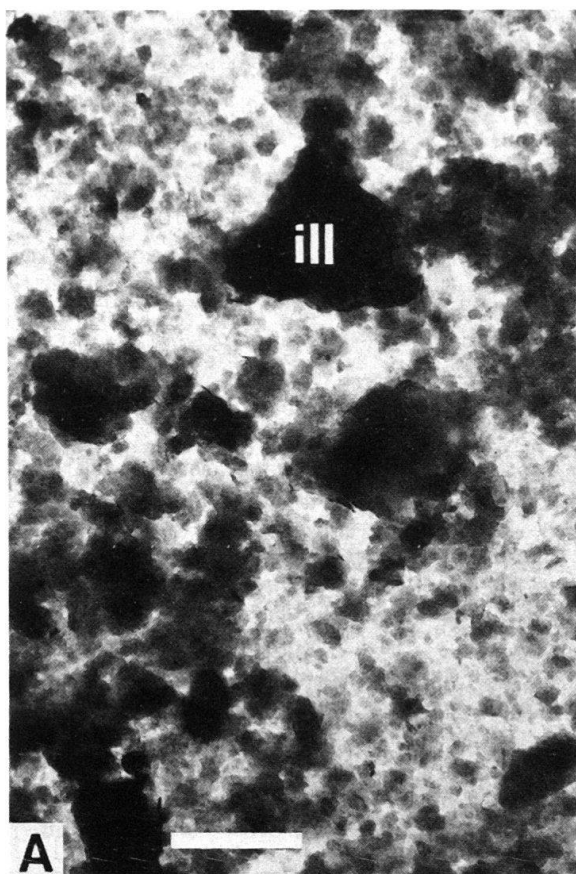


Fig. 6. DTA curves: A: Illite B: Mixture of 85% smectite, 10% illite, 5% mixed-layers.

mineral assemblages (up to 85% smectite). The DTA curves show an endothermic peak around 140 °C corresponding to dehydration. A relatively weak but clearly visible endothermic peak appears around 560 °C (dehydroxylation) and finally, a third endothermic peak can be observed around 890–900 °C, immediately followed by an exothermic reaction at 925 °C (Fig. 6B).

Magnesian (trioctahedral) smectites are characterized by no or only a weak endothermic peak around 500–600 °C and by an endothermic peak around 800–850 °C. Aluminous and ferriferous (dioctahedral) smectites show a clear reaction between 550 and 700 °C. Moreover, the third endothermic peak reaches its maximum around 860–960 °C (CHANTRET et al. 1971). Compared with these data, Purbeckian smectite seems to be dioctahedral and belongs to the Wyoming type. Furthermore, the attenuated endo-exothermic reaction (Fig. 6B) indicates Al-Fe-rich smectite (CHANTRET et al. 1971).



### *Geographical distribution of clay minerals*

Mean values of the clay-mineral associations are calculated and plotted for each section (Fig. 8). The main clay assemblages are distributed in two geographic areas:

- the first one in the northwestern part of the Jura is characterized by clay assemblages mainly composed both of illite and smectite;
- the second one in the southeast shows illite-rich clay assemblages. Only small amounts of mixed-layers are associated with the illite, and their mean proportions decrease southward. Smectite never occurs.

The sections SC, CG and La appear to belong to the illite-rich type of assemblages (Fig. 8). However, as these sections are incomplete and only few samples have been analyzed, the values represented on Figure 8 are not necessarily significant.

## 4. Discussion

### *Influence of burial diagenesis*

During early stages of burial diagenesis, smectites are generally replaced by mixed-layers (DUNOYER DE SEGONZAC 1969, HOWER et al. 1976, KISCH 1983) and in some cases, as in the subalpine area, diagenesis of clay minerals can be expressed by relationships between lithology and clay mineralogy (DECONINCK 1987). The abundance of poorly crystallized smectites in many sections, the lack of chlorite even in limestone beds, and the independence of clay mineralogy from lithology therefore suggest very weak, or no influence of burial diagenesis. Even in sections showing illite-rich clay assemblages in the Purbeckian, the underlying formations contain smectites, indicating that burial diagenesis did not occur. The stratigraphic column of the Jura given by TRÜMPY (1980) shows that the maximum burial depth of the Purbeckian amounted to about 1000 m. In general, the influence of burial diagenesis on clay mineral associations appears negligible in the Jura Mountains (PERSOZ & REMANE 1976, PERSOZ 1982, DECONINCK 1984).

### *Origin of smectite and palygorskite*

Smectites in sediments can have various origins, e.g., volcanogenic, pedogenic, authigenic. There is no evidence for volcanic influence during the Purbeckian. On the other side, authigenic smectites are well-known in evaporitic environments and in lakes or lagoons protected from major detrital input, such as they existed in the Purbeckian. TRAUTH (1977) described the following clay mineral suite from evaporitic basins: Al-Fe-smectites (Wyoming type) are found associated with detrital input. As carbonate sedimentation becomes dominant, Al-Mg-smectite (Cheto type) appears. Then, Mg-smectites (saponite and stevensite) progressively replace detrital Al-Fe-smectites. When detrital input is quasi-absent, authigenic fibers of palygorskite and sepiolite are formed. As a

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Fig. 7. TEM micrographs, scale bars 0.5  $\mu$ m. A and B: Purbeckian illite (95% illite, 5% mixed-layers). Note the fleecy aspect of the tiny particles of illite. Scarce particles which show well defined limits (ill) are probably detrital. C. Mixture of chlorite (traces), illite (55%), mixed-layers (5%) and smectite (35%). Rare particles of illite seem to be detrital (ill), others are undistinguishable from smectite. D. Fibers of palygorskite (5–10%) associated with illite and smectite. Short and broken fibers suggest reworking.

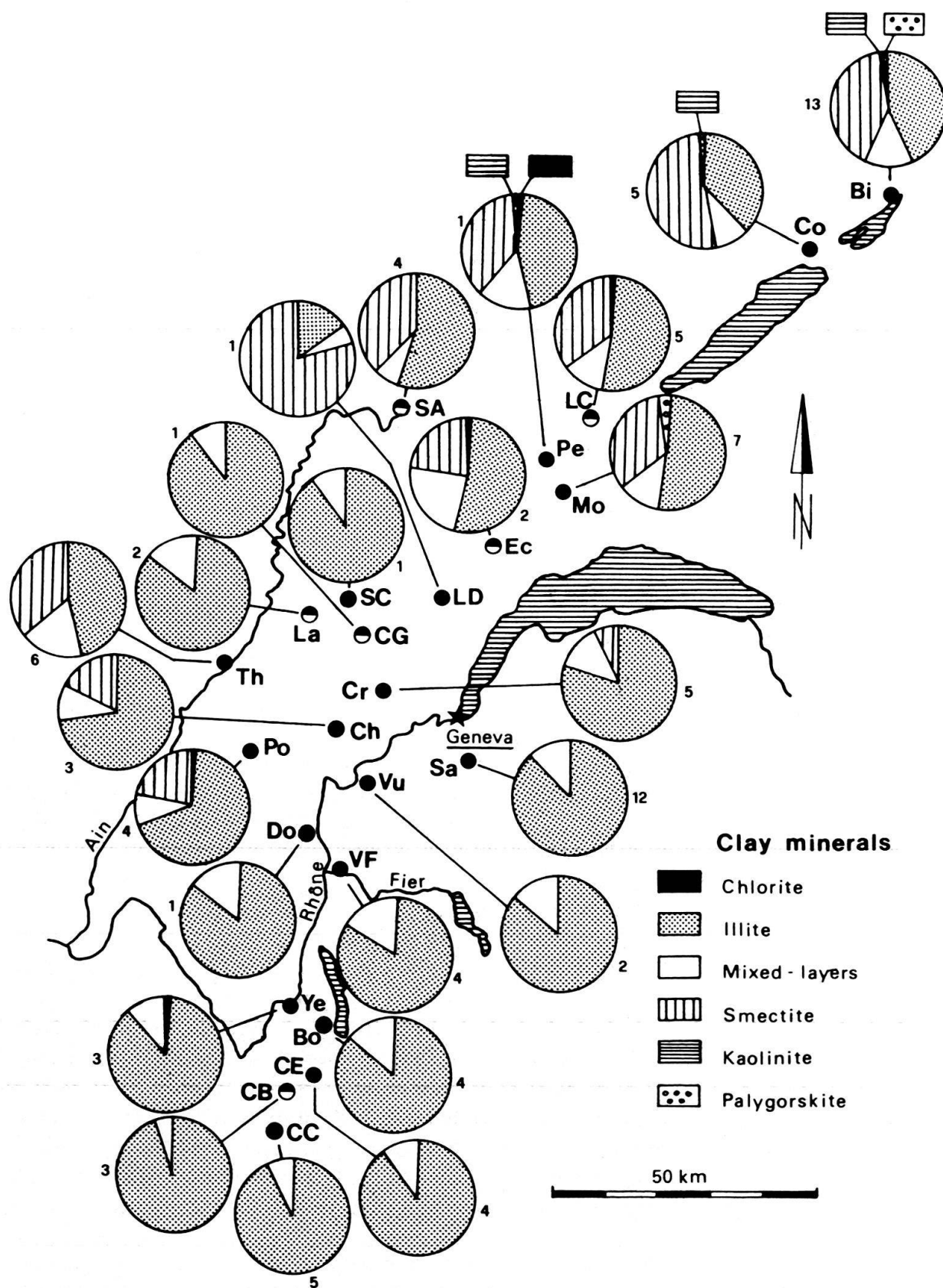


Fig. 8. Geographical distribution of mean clay-mineralogical assemblages of the Purbeckian facies (same legend as in Figure 1, numbers indicate amount of samples represented).

matter of fact, palygorskite (which is unusual in Mesozoic formations of the western Tethys ocean; CHAMLEY & DECONINCK 1985) has been found in some samples of Purbeckian facies (PERSOZ & REMANE 1976; this investigation, Fig. 7D). This is consistent with the presence of evaporites in the Purbeckian suggesting high ionic concentration and environments favorable to development of authigenic minerals such as Mg-smectites. However, DTA analyses point to Al-Fe-smectites. The short and broken fibers of palygorskite (Fig. 7D) probably indicate reworking. This suggests a detrital rather than an authigenic origin. The Al-Fe-smectites are widespread in Mesozoic series and probably derived from gentle soil erosion, as it has been described by PAQUET (1970) from vertisols actually developing in continental downstream zones, under hot and seasonally humid climates.

### *Origin of illite*

The Purbeckian illite has a chemical composition intermediate between typical illite and glauconite (Fig. 5). Chemical and DTA analyses show many similarities with those described by GABIS (1963) and called "illite ferrifère". Fe-rich illites have been reported from rocks of various ages: Upper Devonian (KOSOVSKAYA & DRITS 1970), late Jurassic (KELLER 1958), Eocene–Oligocene (JUNG 1954, GABIS 1963, PORRENGA 1968, DECARREAU et al. 1975, ESTEOULE-CHOUX 1984), and pre-Wisconsin (PARRY & REEVES 1966). These illites are often associated with green marls and gypsum, as it is the case in the Purbeckian of the Swiss and French Jura. They have been successively called "illite ferrique", "glauconitic mica", "glauconie", "illite ferrifère", and "glauconitic illite" (PORRENGA 1968).

The origin of glauconitic illite is not clear. A formation by direct precipitation has been proposed by JUNG (1954) and ESTEOULE-CHOUX (1970, 1984), but most authors think that it forms by alteration of montmorillonite (smectite) in lacustrine or lagoonal environments. SINGER & STOFFERS (1980) describe transitions of smectite to illite-smectite mixed-layers, and finally to illite in two East African lakes. Illitization of smectites seems to be caused by saline paleo-lake water with high K/Na ratios:  $K^+$  necessary for illitization probably came from the transition of K-Na zeolite to analcime. These authors equally notice that illite particles are undistinguishable from smectites, as it is the case in the Purbeckian.

Detrital illites are generally associated with terrigenous material and reflect physical alteration of continental land masses (MILLOT 1964). Purbeckian facies are composed almost entirely of limestones and dolomites with very little terrigenous material, and must have been deposited in environments protected from important detrital input. Typically detrital minerals like kaolinite and quartz are virtually absent. It is also difficult to explain a monomineralic clay fraction composed entirely of detrital illite, as strong erosion generally affects soils and rocks of various types and ages. In case of important detrital input, mineralogical assemblages are marked by a rather great diversity of clay minerals. Moreover, the high Fe-content of Purbeckian illites does not imply a detrital origin. Detrital sediments rather contain aluminous illite or muscovite produced by erosion of older rocks. Finally, the shapes of Purbeckian illites (Fig. 7A, B) differ significantly from those of detrital illites. These facts and the review of the literature cited above suggest that *most Purbeckian illites are not detrital but have an authigenic origin*. They probably replaced smectites resulting from soil erosion in downstream land areas under hot and

humid, seasonally contrasted climates (PAQUET 1970). Intermediate stages of the transition from illite to smectite clearly appear on the XRD diagrams of most samples where illite-smectite mixed-layers with various proportions of both single minerals can be observed. The high Fe-content of Purbeckian illite can therefore be explained by high Fe-content of the original detrital smectites.

The intensity of smectite-to-illite transitions depends on  $K^+$  availability and on  $K^+$  concentration in the depositional environment. In normal marine waters, the concentration of  $K^+$  is too low, and transitions of smectite to illite do not occur. In the subalpine realm for example, clay minerals of sedimentary series at the Jurassic–Cretaceous boundary are mainly composed of illite, smectite and kaolinite of detrital origin (PERSOZ & REMANE 1976, DECONINCK et al. 1985). On the other hand, Purbeckian semi-closed basins were temporarily in contact with marine waters and submitted to intense evaporation. In this context,  $K^+$  concentration could increase and favor transitions of smectite to illite. Frequent contacts of smectites with  $K^+$ -rich marine waters were possible due to periodic marine incursions which then were followed by evaporation under hot Purbeckian climates. Such wetting and drying cycles have been proposed by SRODON & EBERL (1984) and EBERL et al. (1986) to explain smectite to illite transitions in natural environments. Wetting and drying cycles probably affected Purbeckian green marls which were exposed at the top of shallowing-upward sequences. The higher proportions of illite in the southeastern part of the Jura Mountains (Fig. 8), i.e., towards the Subalpine Basin which was open marine during Jurassic–Cretaceous times, probably resulted from more frequent contacts with marine waters in this area. In the northwestern region, detrital smectites are partly preserved as  $K^+$  supply was less pronounced.

#### *Purbeckian clay minerals of other areas*

There are few clay-mineralogical data available for the Purbeckian facies. In France, Purbeckian clay minerals have been investigated in the Boulonnais (North of France; DECONINCK et al. 1982) and in the Berry region (Paris Basin; DEBRAND-PASSARD 1982). In contrast to the Jura Mountains, kaolinite occurs together with illite and smectite. In England, Lower Purbeck beds contain illite and smectite as in the Purbeckian of the Jura Mountains. Kaolinite becomes important only in the Middle and Upper Purbeck. Kaolinite probably came from the Anglo-Brabant massif which was tectonically rejuvenated at the corresponding period (SLADEN 1983, SLADEN & BATTEN 1984). A similar origin is possible for the kaolinite of Purbeckian facies in the Boulonnais, as clay mineralogy of the underlying formations (Kimmeridgian–Portlandian) mainly reflects active tectonics on adjacent land masses (e.g., Ardennes ridge; DECONINCK et al. 1982). In Spain (Camos Basin) we have investigated only two samples of Purbeckian facies which are mainly composed of smectite. Kaolinite is present in small quantities.

Occurrence of kaolinite in the Anglo-Parisian Basin is in agreement with large detrital input into this area (COLIN & OERTLI 1985). Detrital material including kaolinite originating from ancient massifs might have been caught in this basin while a small proportion of clays, mainly composed of pedogenic Al-Fe-smectites, settled out on the Jurassic carbonate platform. This partly results from differential settling processes which favored proximal deposition of illite and kaolinite, and the exportation of the small-sized particles of smectite far from their source-area (GIBBS 1977). Small and local inputs of detrital material occurred in the very northern part of the study area (Bienne, Fig. 3).

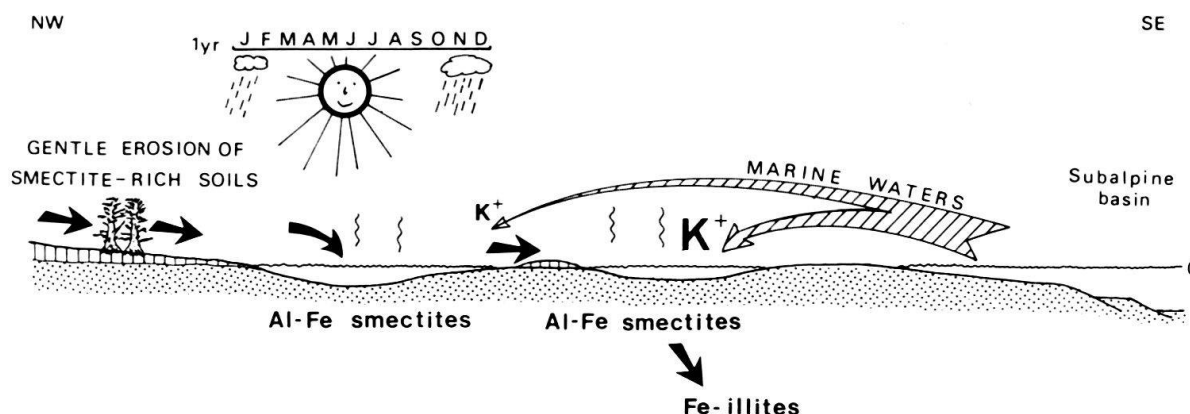


Fig. 9. Hypothetical depositional and environmental setting of Purbeckian clay minerals.

### *Depositional setting of Purbeckian clay minerals*

From the available data on Purbeckian clay minerals it appears that detrital input, differential settling processes, and smectite-to-illite transitions controlled their geographical distribution.

Detrital input came from emergent land masses, where erosion affected both rocks and soils. Older rocks mainly furnished illite and perhaps kaolinite. Smectite, but also kaolinite, probably originated from soils. Smectite formed in downstream zones, while kaolinite mainly developed in upstream areas. If detrital input was dominant, as in the Anglo-Parisian Basin, clay-mineralogical assemblages are quite varied.

Differential settling processes led to the deposition of illite and even more of kaolinite in near-shore environments. Higher floatability of smectite allowed its dispersion over wide areas. Smectite and small quantities of illite could reach the shallow-water Jurassic platform where they settled out. On emergent parts of this low-relief platform, smectite-rich soils could also develop and supply Purbeckian lagoons and lakes with terrigenous material (Fig. 9).

Smectite-to-illite transitions occurred in the southeastern part of the Jura Mountains where smectites had been deposited on the shallow-water Purbeckian platform. There they were probably submitted to repetitive wetting by  $K^+$ -rich marine waters and drying under a hot climate (Fig. 9). When such a mechanism is dominant it leads to monomineralic illitic clay assemblages. During a following transgressive event, Fe-rich illites were partly reworked and incorporated in the overlying limestone beds.

## **5. Conclusions**

Clay-mineral assemblages of the Purbeckian green marls are geographically well defined. In the northwestern part of the Jura Mountains, clay minerals mainly consist of illites and detrital Al-Fe-smectites. In the southeastern part, clay-mineral assemblages are composed almost entirely of pure authigenic, Fe-rich illite.

Detrital smectites derived from the gentle erosion of soils where they had formed in downstream continental zones under a hot and seasonally humid climate. As Purbeckian green marls occur at the top of shallowing-upward sequences and are often associated with features indicating subaerial exposure (such as desiccation fissures, evaporites,

calcrete and black pebbles), smectites were probably submitted to cyclic wetting by  $K^+$ -rich marine waters and subsequent drying. This mechanism which may lead to transitions of Al-Fe-smectite to Fe-rich illite was particularly well developed in environments frequently in contact with marine waters, i.e., areas in contact with the Subalpine Basin. Therefore, Fe-rich illites indicate partial emersion close to marine realms and can be useful for paleogeographic reconstructions. Fe-rich illites are also characteristic (as indicated by faunas found in the green marls) of intermediate continental-marine areas. Fe-illites are often encountered in the late Jurassic and Oligocene (e.g., PORRENGA 1968), and seem to be associated to subaerial exposure of carbonate platforms due to world-wide regressions. Green marls bearing Fe-rich illite are therefore characteristic of small-scale as well as large-scale regressions.

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