Stratigraphy and mineralostratigraphy of the Kimmeridgian in the central Jura mountains of Switzerland and eastern France

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Stratigraphy and mineralostratigraphy of the Kimmeridgian in the central Jura mountains of Switzerland and eastern France[1]

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Key words: Kimmeridgian, microfacies, mineralostratigraphy, kaolinite, major discontinuities, Jura mountains
Mots clefs: Kimméridgien, microfaciès, minéralostratigraphie, kaolinite, discontinuités majeures, Jura

ABSTRACT

The microfacies, micropaleontology, mineralogy and sedimentology of the series of the Reuchenette Formation (Kimmeridgian), introduced by Thalmann (1966) to replace the Kimmeridgian auctorum, have been studied and compared with other series in the Swiss and French Jura Mountains. The studied area corresponds to a shoal environment separating the Tethys (S) and the Paris Basin (N). The depositional environments represent three major domains: intertidal/supratidal domain, internal platform and external platform (margin and slope). Field observations and microfacies analysis revealed two major discontinuities. Clay-mineralogy data show that kaolinite can be used as a stratigraphical marker. Both methods, microfacies and clay-mineralogy, allowed to establish correlations in an area where the biochronological markers are extremely rare. The two major discontinuities can be correlated with series described by Bernier (1984), Chevallier (1989) and Strohmenger et al. (1991) in the Jura of SE France (Jura méridional) and can be tied to the global eustatic curve established by Haq (1991).

RESUME

Les séries kimméridgiennes, très pauvres en éléments biologiques de datation ont été étudiées sous leurs aspects microfaciologiques, micropaléontologiques, minéralogiques et sédimentologiques. L'étude inclut la localité-type de la Formation de Reuchenette, introduite par Thalmann (1966) pour remplacer le Kimméridgien auctorum. Ces séries, principalement calcaires, ont été ensuite comparées avec les séries du Jura suisse et français. Le domaine étudié correspond à un haut-fond séparant la Téthys (S) du Bassin de Paris (N). Les environnements de dépôt représentent trois domaines majeurs: domaine margino-littoral, plate-forme interne et plate-forme externe (bordure et talus externe). L'analyse des microfaciès a permis de mettre en évidence deux discontinuités majeures. L'analyse minéralogique a permis d'identifier la kaolinite comme marqueur minéralostratigraphique. Grâce à l'étude combinée des microfaciès et des minéraux argileux, il a été possible d'établir des corrélations fiables pour l'ensemble du domaine étudié. Les deux discontinuités majeures se corrèlent avec les séries du Jura méridional décrites par Bernier (1984), Chevallier (1989) et Strohmenger et al. (1991) et peuvent être reliées avec la courbe eustatique globale de Haq (1991).

Introduction

Thurmann (1832) introduced the name Kimmeridgian as one of the stratigraphic subdivisions of the Jura Mountains' Upper Jurassic by naming "Kimeridgian Marls" the "Beds with Pteroceras". These were placed as 2nd division in the lower part of the Portlandian Group (Fig. 1).

Marcou (1848) divided Thurmann's Portlandian Group into two members: the "Kimmeridge marls" (or "Banné Marls") and the "Kimmeridge Limestones", both considered as purely lithostratigraphic units.

Rollier (1888, 1893, 1898), for the first time, published a complete section of the Malm in the Jura Mountains of the canton Bern. He recognized and delimited three stages: Sequanian (top represented by the "St.-Verena Oolith"), Kimmeridgian (top represented by the "Banc à Nérinées" or the "*Exogyra virgula* Marls") and Portlandian.

Heim (1919) subdivided Rollier's Kimmeridgian in Pterocerian and Virgulian. Heim's Kimmeridgian corresponds to the Lower Kimmeridgian of England, as described by Arkell (1956), finishing with the Aulacostephanus pseudomutabilis Zone. In England, the Middle Kimmeridgian starts with the Gravesia sp. Zone, which, however, following the continental European tradition, defines the base of the Portlandian. The Kimmeridgian *sensu gallico* corresponds thus to the Lower Kimmeridgian in England. Recent studies of *Amoeboceras* faunas (Atrops et al., 1993) have shown that the lower part of the Submediterranean latest Oxfordian Planula Zone correlates with the lower part of the Subboreal Kimmeridgian Baylei Zone and that the lower part of the Submediterranean Kimmeridgian Platynota Zone correlates with the upper part of the Subboreal Baylei Zone (Fig. 2). This indicates that the boundary between the Oxfordian and Kimmeridgian is actual-

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Thurmann (1832)		Marcou (1857-60)	Heim (1919)		Arkell (1956)		Thalmann (1966)	
GROUPE PORTLANDIEN	1. Division Calcaires portlandiens		BONONIEN	PORTLANDIEN	MIDDLE K.	Gravesia spp.	"PORTL."	Twannbach-formation
GROUPE PORTLANDIEN			KIMMERIDGIEN	VIRGULIEN	LOWER KIMMERIDGIAN	Aulacostephanus. autissiodorensis A. eudoxus	"KIMMERIDGIEN"	Reuchenette-formation
GROUPE PORTLANDIEN	2. Division Marnes kimméridiennes	Calc. du Banné Marnes du Banné	KIMMERIDGIEN	PTEROCERIEN	LOWER KIMMERIDGIAN	A. mutabilis Rasenia cymodoce Pictiona baylei	"KIMMERIDGIEN"	Reuchenette-formation
GR. CORALLIEN	3. Division Calcaires à Astartes	SEQUANIEN	LUSITANIEN	SEQUANIEN	UPPER OXFORD.	Rinsta edia pseudocordata	"SEQUANIEN"	Verenaschichten

Fig. 1. Subdivisions of the Malm from Thurmann (1832) to Thalmann (1966).

ly drawn at a higher level in the Submediterranean zonal scheme than in the Subboreal one. The Kimmeridgian of this study is used in the classical *sensu gallico.*

Biological markers (ammonites, foraminifera) are very rare in these series and, therefore, precise chronostratigraphical correlations are difficult to establish. One ammonite (*Phylloceras* cf. *tenuisculptum*) of Kimmeridgian age was found at Morillon (Fig. 3, 4). The charophytes (*Echinochara pecki, Porochara* sp.) indicate also a Kimmeridgian age for these series but are of no use for more accurate correlations. The combined first appearance of *Clypeina jurassica* and *Campbelliella striata* in the studied series can be used as a complementary tool for correlations (Strohmenger et al. 1991). According to Gygi (1995) a find of *Aspidoceras* cf. *acanthicum* just above the Virgula Beds at Alle (canton Jura) indicates a late Kimmeridgian age for strata classically placed in the earliest Portlandian. It appears thus that, in the Jura Mountains, both Kimmeridgian and Portlandian were never precisely dated with biostratigraphic markers. The names Oxfordian, Kimmeridgian and Portlandian have classically been used in an approximate chronostratigraphical sense. The conventional boundaries of these "stages" correspond to lithological markers which are supposed to be more or less isochronous and to correspond to the international stage boundaries.

		Europe Subboreal	Europe Submediterranean
Upper Kimmeridgian	*sensu gallico*	*Autissiodiorensis*	*Beckeri*
		Eudoxus	*Eudoxus*
		Mutabilis	*Acanthicum*
Lower Kimmeridgian	*sensu gallico*	*Cymodoce*	*Divisum*
			Hypselocyclum
		Baylei	*Platynota*

Fig. 2. Comparison between the Submediterranean and Subboreal ammonite Zones.

Thalmann (1966) introduced the name of "Reuchenette Formation" for the Kimmeridgian strata of the Swiss Jura mountains. This formation is defined by the same lithostratigraphical boundaries as used by Rollier (1888) nearly a century ago.

Bernier (1984) and Chevallier (1989) recognized and described several formations of Kimmeridgian age *(sensu gallico)* in France. Most of these (like "Calcaires et Marnes de Chargey", "Calcaires et Marnes de Matafelon", etc.) are not easily recognizable in the field outside road cuts. They have no direct equivalent in Switzerland.

Only the following formations or layers are clearly and easily recognizable by their lithology (Fig. 1): the "St.-Verena Oolith", the "Banné Marls", the "Banc à Nérinées" and the "*Exogyra virgula* Marls". The "Reuchenette Formation" does not possess a characteristic lithological content (Gygi 1995) but its limits are clearly identifiable, in a part of the studied region.

Persoz & Remane (1973, 1976) analysed the microfacies and the mineralogy (by X-ray diffraction) in series extending from the Dogger to the Malm in the central Swiss Jura Mountains (Canton Neuchâtel). Persoz (1982) based his Oxfordian and Kimmeridgian correlations on the variations of the kaolinite content. For this author, the kaolinite variations reflect changes in the sedimentary input and are thus independent from facies changes. This allows kaolinite to be used as a chronostratigraphical marker.

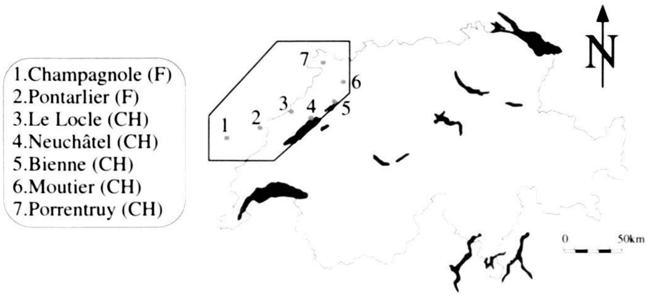


Fig. 3. General situation of the studied area.

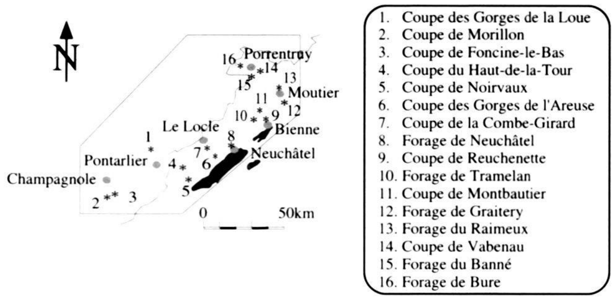


Fig. 4. Location of outcrops and drillholes.

The purpose of this work is to revisit Kimmeridgian stratigraphy of the Central Jura Mountains by using microfacies, clay-mineralogy and sequence stratigraphy (correlations through major discontinuities).

Regional settings

Sixteen outcrops and diamond drillcores located in the Jura mountains of NW Switzerland and E France (Fig. 3, 4) have been analysed. The studied area corresponds paleogeographically and sedimentologically to a carbonate shelf separating the Tethys (S) from the Paris Basin (N). This shelf is influenced by two major islands: the Massif Central (SW) and the Ardennes-Vosges-Black Forest (NE). The climate is tropical to subtropical according to Auboin et al. (1988).

Material and methods

Samples were taken at irregular intervals in order to document changes in lithology. Additional samples were taken to ascertain an appropriate coverage of lithologically monotonous intervals. This procedure resulted in a mean sampling distance of 40 cm. All samples (nearly 1700) have been studied in thin section to determine the microfacies. The mineralogy (whole rock and clay mineralogy) of almost 550 samples has been analysed at the Geochemistry Laboratory of the University of Neuchâtel using a Scintag™ 2000 diffractometer. The methods of mineralogical analysis and principally those of clay minerals are based on the works of Brindley & Brown (1980), Adatte & Rumley (1984, 1989), Adatte (1988) and Moore & Reynolds (1989). Each sample was decarbonated, separated into two fractions (< 2 μm and 2–16 μm), and then analysed by X-ray diffraction (Scintag™) following the procedure described by Kübler (1987). The two grain size fractions (< 2 μm and 2–16 μm) were obtained using a timed settling method (based on Stokes law) described by Rumley & Adatte (1983). XRD analysis was made on oriented clay samples (< 2 μm and 2–16 μm fractions). The samples were first dried at room temperature and placed in ethylene-glycol solvated conditions after the first XRD analysis. The intensities of selected XRD peaks characterizing each mineral (clay or grain) present in the fraction (e.g. mica, kaolinite, mixed-layers, quartz) are given in raw values (CPM, coups par minute). Content in swelling (% smectite in mixed layers) is estimated by using the method of Moore & Reynolds (1989).

The five most representative sections (presenting different formations, variations in the microfacies curve and the mineralogical content) were selected for this paper: Morillon, Gorges de la Loue, Gorges de l'Areuse, Reuchenette and Vabenau.

Sedimentology

The terminology used for the description of the thin sections is derived principally from Folk (1959, 1962), Dunham (1962), Flügel (1982) and Tucker & Wright (1990).

Microfacies

The study of thin sections allowed to recognise four major depositional environments (slope, platform margin, internal platform and intertidal/supratidal domain) on this carbonate shelf. These four domains are represented by sixteen microfacies (Fig. 5). The microfacies FT corresponds to the "faciès de transgression" (= mixed facies) described by Arnaud-Vanneau (1980). It occurs above discontinuities. This microfacies is arbitrarily placed in the external platform (platform margin) because of its similarities with the other microfacies representing this environment.

Slope (external platform)

Five microfacies numbered F1 to F5 represent this environment. Although differing in details, they belong all to a relatively calm environment, characterized as open marine by its fauna (especially echinoderms). Mudstones, and more rarely wackestones, containing spicules, large angular fragments of echinoderms and shells, serpulids and foraminifera like *Alveosepta* sp. and *Lenticulina* sp. characterize this domain. (refer to Fig. 6, pict. a, b for microfacies F1 and F5).

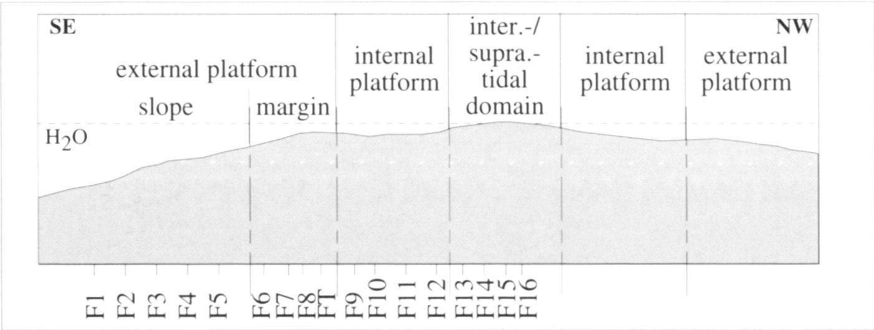


Fig. 5. Location of the different microfacies on the Kimmeridgian carbonate shelf.

Platform margin (external platform)

Three microfacies (F6 to F8) represent this environment. Grainstones and packstones containing mainly ooids and/or peloids indicate high energy environments, small rounded fragments of echinoderms and shells, foraminifera like *Nautiloculina oolithica* characterise this domain as open marine. (refer to Fig. 6, pict. c for microfacies F7).

Internal platform

This domain is separated in an outer part and an inner part.

The outer part is represented by two facies (F9–F10). Grainstones and packstones containing small echinoderm debris, foraminifera and algae indicative of shallow waters *(Cayeuxia, Marinella)* characterize this domain.

The inner part is represented by two microfacies (F11–F12; refer to Fig. 6, pict. d for microfacies F11). Wackestones containing oncoids, foraminifera (miliolids, *Siphovalvulina* sp.), dasycladacean algae *(Campbelliella striata, Salpingoporella annulata, Clypeina jurassica)* characterize this domain. Echinoderm debris are absent, which indicates more or less restricted environments.

Intertidal/supratidal domain

Four microfacies (F13–F16; refer to Fig. 7, pict. e, f, g for microfacies F14 and F16) represent this environment. Grainstones with keystone-vugs and mudstones with birds-eyes, charophytes (*Echinochara pecki, Porochara* sp.) and/or ostracods characterize this domain.

"Faciès de transgression" (= mixed facies, FT)

This facies is represented by grainstones containing rounded and angular black pebbles and many micritized rounded echinoderm debris (Fig. 7, pict. h).

Refer to Figure 8 for the paleoecological distribution of foraminifera, algae and other elements characterising each environment.

Microfacies analysis

Rapid and important variations in the vertical succession of microfacies reveal major discontinuities. These discontinuities are then used for a tentative sequence stratigraphic interpretation sensu Vail et al. (1977, 1987).

By definition (Arnaud & Arnaud-Vanneau 1994), a discontinuity is located between two layers if there is a lack in sedimentation due to non-deposition, alteration, dissolution or erosion. In this study, three types of discontinuities have been distinguished.

Major discontinuities

They are lithologically well marked (erosional surfaces forming a hard-ground, karstification). The microfacies show rapid and important variations across the discontinuity. A good example is given by the outcrop of Gorges de la Loue where karstification is remarkably developed. The deposit overlying the discontinuity is a limestone containing black pebbles and showing graded bedding (Fig. 9).

Minor discontinuities

Recognisable only in the outcrop, minor discontinuities are generally represented by uneven hard-grounds underlining relatively minor lithological changes. The succession of microfacies does not show significant changes.

Emersive horizons

This third type of discontinuity is represented by intertidal to supratidal limestones with charophytes, ostracods, birds-eyes and/or algal mats. They show no traces of erosion and are rarely linked to important lithological changes and/or variations in the microfacies curves. Emersive horizons present rhythmic intercalations in the outcrops of Gorges de l'Areuse and Reuchenette.

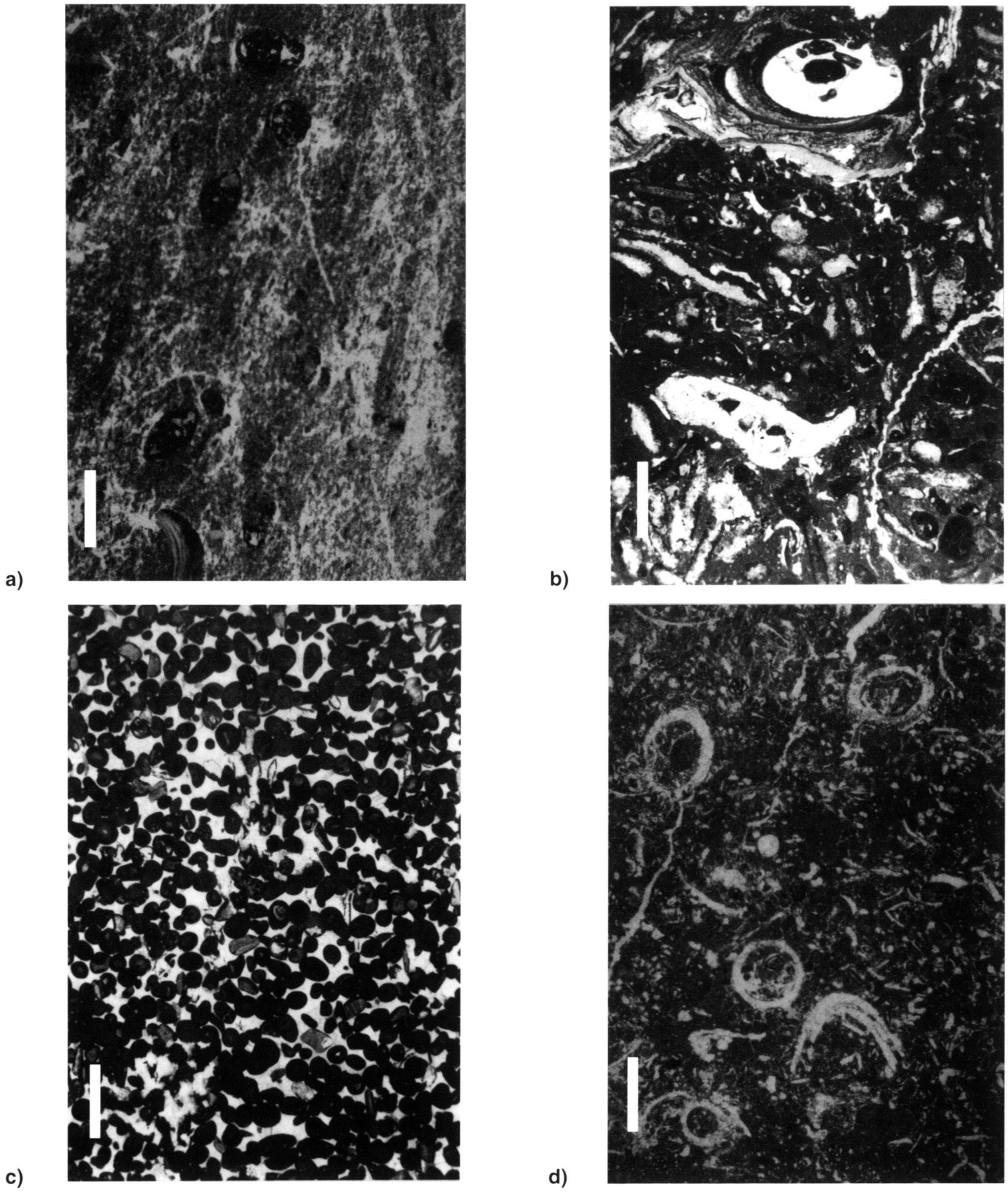


Fig. 6. Microfacies of the Kimmeridgian shelf. (bar = 1 mm).

Picture a F1 = marly micrite, shell debris and foraminifera (*Alveosepta* sp.). Texture: mudstone/wackestone.

Picture b F5 = biomicrite with large shell debris, echinoderms, serpulids and foraminifera (*Alveosepta* sp. and *Lenticulina* sp.). Texture: wackestone/packstone.

Picture c F7 = oosparite, echinoderms, micritised shells and foraminifera (*Nautiloculina oolithica*). Texture: grainstone.

Picture d F11 = biomicrite rich in dasycladacean algae *(Campbelliella striata, Salpingoporella annulata, Clypeina jurassica)* and micritised shell remains. Few foraminifera (miliolids, *Siphovalvulina* sp.). Texture: wackestone.

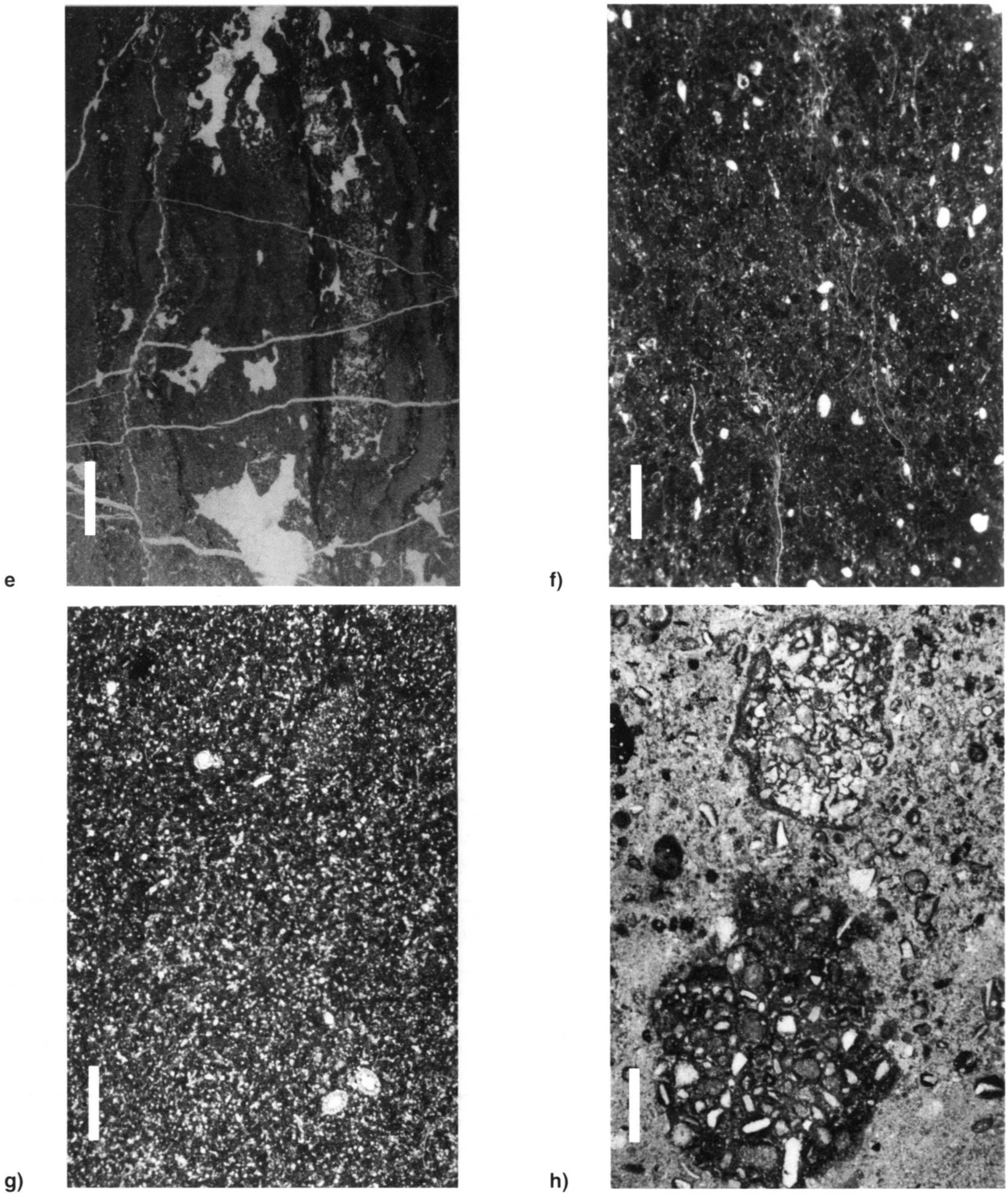


Fig. 7: Microfacies of the Kimmeridgian shelf. (bar = 1 mm).
Picture e F14 = algal laminated micrite with fenestral structures. Bioclasts very rare. Texture: mudstone/boundstone.
Picture f F16 = micrite, ostracods. Texture: mudstone/wackestone.
Picture g F16 = micrite, charophytes (*Echinochara pecki, Porochara* sp.) and/or ostracods indicating fresh water deposits. Texture: mudstone/wackestone.
Picture h FT= sparite, black pebbles and micritised echinoderm debris.
Texture: grainstone.

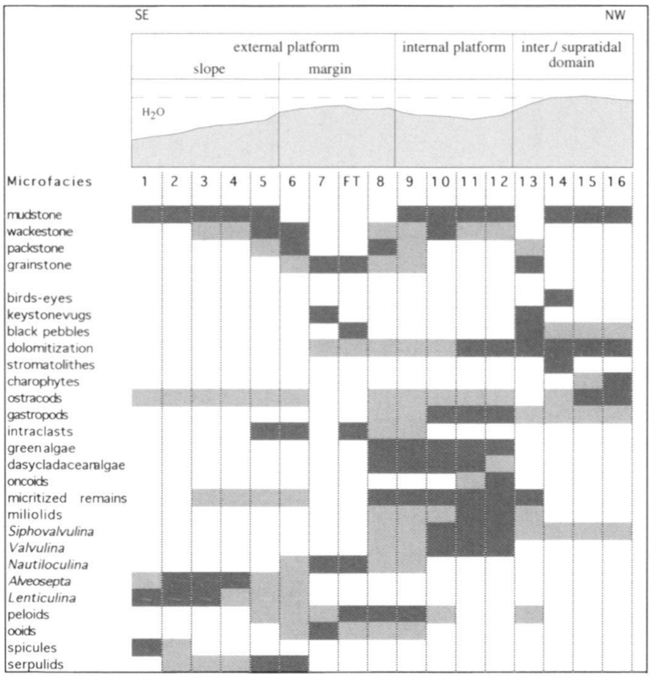


Fig. 8. Distribution of the different elements, foraminifera and algae on the Kimmeridgian carbonate platform. The darker zones show the characteristic locations of the different elements. The brighter zones show the total distribution of the elements on the theoretical carbonate platform during Kimmeridgian time. Note that a microfacies is rarely defined by a single criterion.

Microfacies curves and description of sections

The microfacies curves from five selected sections (Morillon, Gorges de la Loue, Gorges de l'Areuse, Reuchenette and Vabenau) are represented in Figure 10. For reasons of presentation only the discontinuities used in regional correlations (named D1 and D2) are described in this paper.

Gorges de la Loue

The Gorges de la Loue section is situated about 20 km N of Pontarlier (France), alongside the road N67 to Ornans. This profile was already measured and described by Chevallier (1989). The total thickness of the series is about 80 m, showing the Oxfordian-Kimmeridgian transition. The microfacies curve shows external facies in the lower part of the succession, up to the "Calcaires de la Loue". Internal facies are more dominant in the upper part, especially in the "Tidalites d'Arc-sous-Cicon" and the upper part of the "Calcaires et Marnes de Savoyeux". Minor and major discontinuities have been recognized in the Gorges de la Loue series. Discontinuity D1 is located at the top of bed n° 14 and is indicated by a strongly eroded surface forming a hard-ground (karstification), overlain by limestones representing mixed-facies (black pebbles breccia showing graded bedding, see Fig. 9). The microfacies curve shows an important and rapid change across this level: external platform – erosion – internal platform. This discontinuity is placed in the Divisum-Acanthicum Zone by Chevallier (1989). The level of D2 is not attained in this section.

Morillon

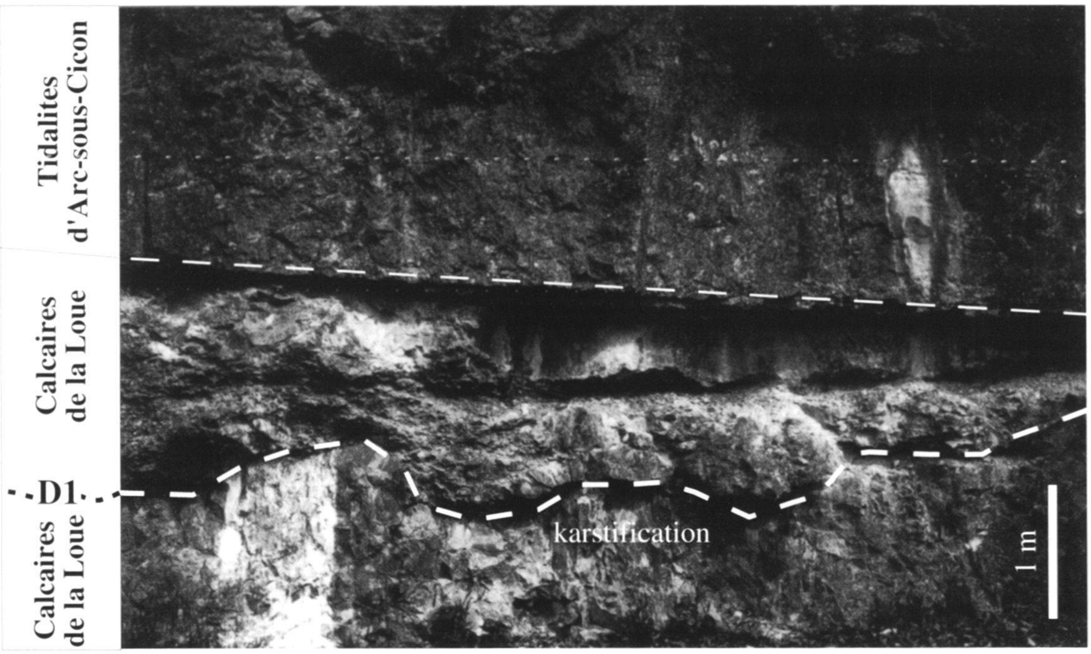
The road cut is situated about 25 km S of Champagnole (France), alongside the road N5 to Morez. The total visible thickness is about 70 m and represents the Oxfordian-Kimmeridgian transition. The upper part of the profile shows tectonic complications. As the different French formations are not very clearly defined, it was not possible to recognize the formations described in the Gorges de la Loue section. The microfacies curve shows, as at Gorges de la Loue, external facies in the lower part of the series, with minor and major discontinuities. The similarities between the microfacies curves in the Gorges de la Loue and Morillon, supported by the variations of the kaolinite content, suggest to place D1 at the top of bed n° 25 in the Morillon series. As at Gorges de la Loue, internal facies are more abundant above D1. D2 is not present in the Morillon section.

Gorges de l'Areuse

The outcrop is situated about 15 km W of Neuchâtel (Switzerland), near the power-station of Combe-Garot (cord. 551.300/201.450, CN 1:50,000 n° 242 Avenches). The total thickness of the series is about 170 m (stratigraphic interval Oxfordian-Portlandian). This outcrop has already been studied by Meia (1965) and Persoz & Remane (1973). The Ste-Verena Oolith is not as well developed as at its type-locality or in the Reuchenette quarry. The top of the "Kimmeridgian" is given by the Banc à Nérinées. The microfacies curve shows a predominance of external facies in the lower part of the series, up to a zone covered by a rockslide and vegetation. Minor and major discontinuities and also emersive horizons have been recognized in the Gorges de l'Areuse series. The dasycladacean association *Campbelliella striata – Clypeina jurassica* appears for the first time in bed n° 42. D1 has not been located precisely in this section but could be concealed by the rockslide. The internal facies are strongly represented above this covered zone, analogous to the above described sections of Gorges de la Loue and Morillon. D2 is placed at the top of bed n° 56. The microfacies curve shows a rapid change from the supratidal domain to the outer part of the internal platform. D2 is located below a *Cladocoropsis mirabilis*-rich bed and the Banc à Nérinées.

Reuchenette

The section is situated about 10 km N of Biel/Bienne (Canton Bern, Switzerland), in the cement-quarry of Péry-Reuchenette (cord. 585.900/226.100, CN 1:50,000 n° 233 Solothurn). The total thickness of the series is about 210 m (stratigraphic interval Oxfordian-Portlandian). This outcrop has already been studied by Rollier (1888), Baumberger (1915), Ziegler (1956)



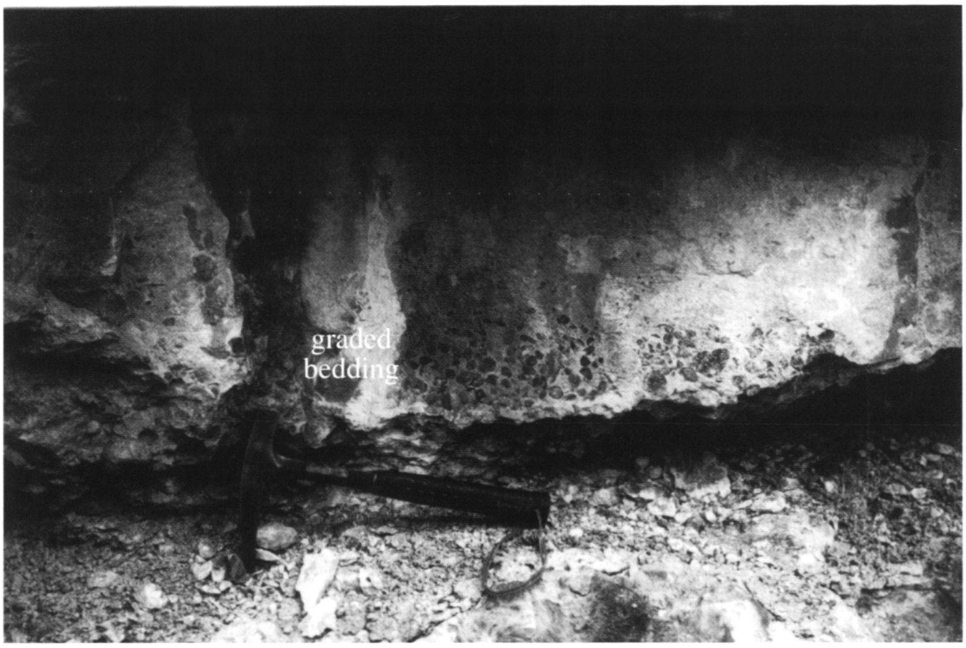


Fig. 9. Gorges de la Loue, major discontinuity D1 overlain by pebbly graded limestones.
Gorges de la Loue, top of the Calcaires de la Loue, karst filling on top of the major discontinuity D1.
Gorges de la Loue, top of the Calcaires de la Loue, detail of the first black pebble graded breccia (bed n°15) overlying the major discontinuity D1.

and Thalmann (1966) who renamed the Kimmeridgian auctorum as Reuchenette Formation. The Ste-Verena Oolith is well developed giving the limit between the Sequanian auctorum (= Upper Oxfordian) and the Kimmeridgian auctorum (= Reuchenette Formation), the top of the Reuchenette Formation is defined here by the *Exogyra virgula* Marls. Minor and major discontinuities and also emersive horizons have been recognized in the Reuchenette series. The microfacies curve shows a predominance of external facies in the lower part of the series, up to D1 and the scree covered zone. Internal facies are predominant in the upper part of this section. The succession of emersive beds, between D1 and D2, looks similar to what was observed in Gorges de l'Areuse (at Combe-Garot). The dasycladacean association *Campbelliella striata – Clypeina jurassica* appears for the first time in bed n° 27. D1 is located at the top of bed n° 19. The microfacies curve shows a rapid variation from the supratidal domain to the outer part of the external platform. The overlying beds are covered by scree. D2 is located at the top of the bed n° 41 (dolomicrite with birds-eyes). The microfacies curve shows a rapid change from the supratidal domain to the outer part of the internal platform and then to the external platform. This discontinuity D2 is located just below a *Cladocorospsis mirabilis*-rich bed as in the Gorges de l'Areuse.

Vabenau

The section is situated about 10 km SE of Porrentruy, near Courgenay (Canton Jura, Switzerland), in a quarry (cord. 574.800/248.200, CN 1:50,000 n° 222 Clos du Doubs). The total thickness of the series is about 25 m (representing the lower part of the Kimmeridgian and the Banné Marls). The limit Oxfordian-Kimmeridgian is not visible. The Banné Marls are very well developed, below them we recognize the Calcaires à ptérocères inférieurs. The series above the Banné Marls are eroded. *Aspidoceras* cf. *acanthicum* was found in the limestone just below the Banné Marls near Courgenay (Gygi & Persoz 1986, Gygi 1995). The microfacies curve shows only small variations within the external platform. D1 is located at the top of bed n° 6, underlying the Banné Marls. D2 is not present in these series.

The microfacies of the different outcrops often correlate well. Detailed correlations between different sections are nevertheless very difficult for two reasons. The first is the frequent lack of biological markers. Only the joint appearance of the dasycladacean algae *Campbelliella striata* and *Clypeina jurassica* can be used as a chronostratigraphic marker (Strohmenger et al., 1991). The second reason is that the different formations of the French Jura Mountains are very difficult or impossible to recognize outside the type-localities, as their limits and lithological content are not clearly defined. Fortunately, mineralogical analyses of the series allowed to complete and confirm the proposed correlations.

Mineralogy

Several mineralogical studies, covering parts of the Upper Jurassic and the Lower Cretaceous have been carried out by Thalmann (1966); Persoz (1982); Viéban (1983), Adatte & Rumley (1984); Gygi & Persoz (1986). However, until now, the Kimmeridgian was not analysed in detail.

The clay-minerals recognized here are: mica, kaolinite, mixed-layers (IS), smectite, chlorite, rectorite. The mixed-layers are generally interstratifications of illite and smectite and form a broad peak on Xray-diffractograms. They have a variable rate of interstratification (between 5–20% smectite) and are irregular. Among grain minerals, quartz, feldspar, pyrite and goethite are present, as already observed by Persoz (1982) and Gygi & Persoz (1986). Rectorite (regular mixed-layer, illite-smectite type) has been observed here for the first time.

The distribution of the observed minerals across the Kimmeridgian carbonate shelf is given in Figure 11. It was obtained by linking the diffraction patterns to microfacies and then averaging the peak intensities of the minerals (after Adatte, 1988).

Mica and kaolinite are the principal constituents of the <2 µm fraction, together with mixed-layers and chlorite. Quartz is rarely present in this size fraction, but is more abundant in the 2–16 µm fraction. Occurrences of smectite are rare and do not follow a regular pattern. Rectorite is more common on the external platform.

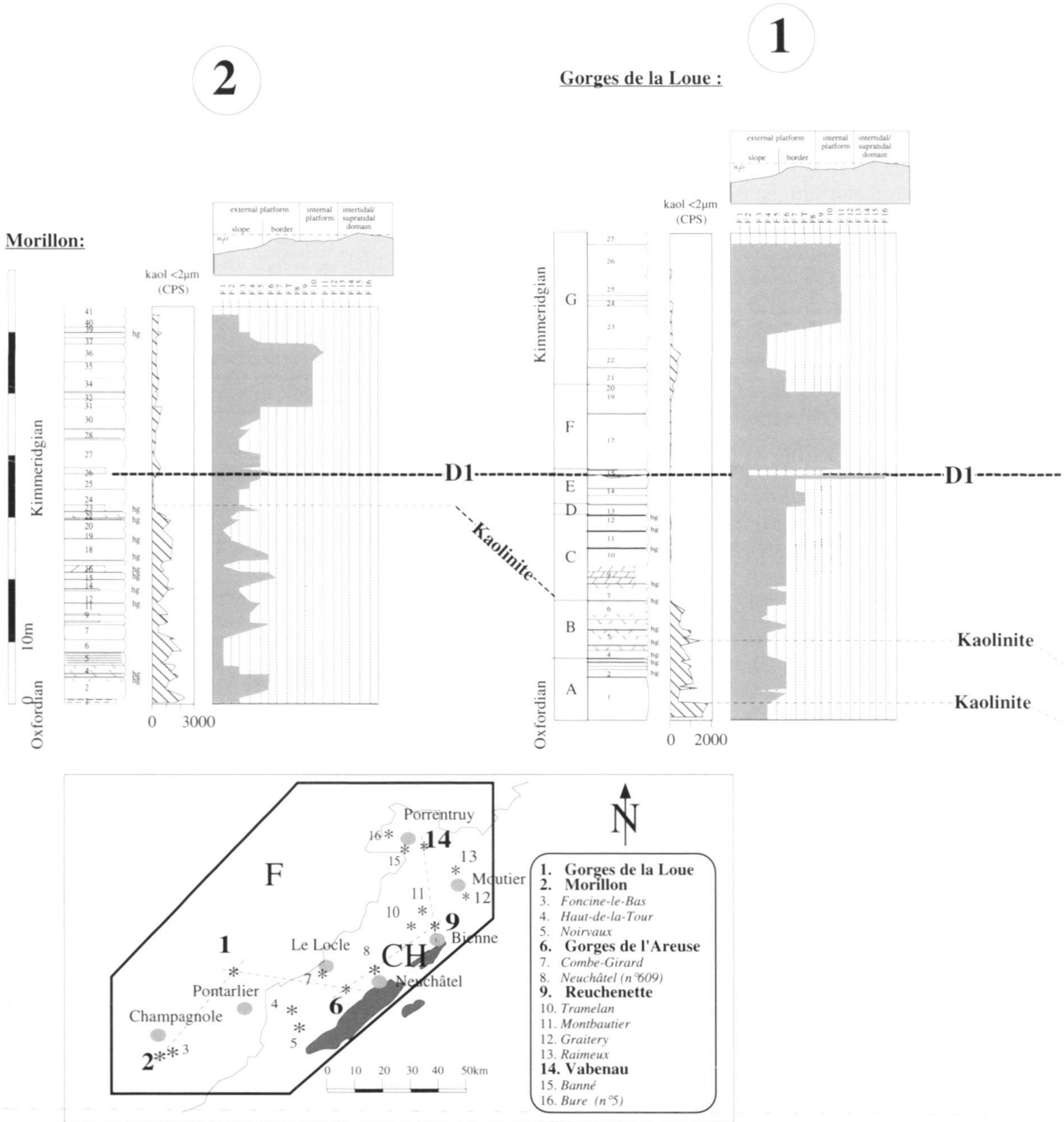
The greatest vertical variations are observed in the kaolinite intensities (from 0–3000 CPS). The kaolinite intensity drops sometimes nearly to zero while the intensities of mica, mixed-layers and chlorite remain rather constant. There is no obvious link between lithology (microfacies) and kaolinite content. The variations of the kaolinite content seem indeed to be independent from the facies and should therefore reflect changes in the original bulk composition of the insoluble residue. The studied area is not too vast so that the presence/absence of this mineral can be considered as isochronous. Therefore kaolinite can be used as a chronostratigraphical marker.

Rectorite

This regular mixed-layer mineral occurs in the < 2 µm size fraction. The main reflections are observed (on ethylene-glycol solvated samples) at 26.6 Å (001*), 13.3 Å (002*) (* = superstructures). The presence of a reflection at 13.3 Å means that the illite-smectite mixed-layer is ordered (R1 ordering, Moore & Reynolds, 1989). Ordering causes the appearance of new reflections containing components of the *001* series of the superstructure.

Content in swelling (% smectite in mixed-layers) is estimated by using the *Δ001/002–002/003* method in °2θ CuKα_1 (Moore & Reynolds, 1989). The two next diffraction patterns (Figs. 12 & 13) show the peaks of mica, mixed-layers and rectorite near 10°2θ CuKα_1, and between 16–17.7°2θ CuKα_1. Δ°2θ = 16.88 – 9.60 = 7.28°, illite percentage is nearly 70% (estimation after Moore & Reynolds 1989, p. 251).

Rectorite is mainly found in micritic and bioclastic limestones of the external platform. The intensity of the *002** peak is generally weak (< 80 CPS). The origin of this mineral can be diagenetic or detrital. Theoretically, rectorite could result from diagenetic transformation of smectite but, according to Ramseyer (1984), the sedimentary cover was not thick enough to allow this transformation. It appears thus that rectorite is of detrital origin like mixed-layers (IS) with low content of swelling layers and smectite.



2
1
Gorges de la Loue :
Morillon:
kaol <2µm (CPS)
external platform
slope
border
internal platform
intertidal/ supratidal domain
Kimmeridgian
Oxfordian
10m
0
0 3000
0 2000
D1
Kaolinite
Kaolinite
Kaolinite
A
B
C
D
E
F
G
Porrentruy
Moutier
Bienne
Le Locle
Neuchâtel
Pontarlier
Champagnole
F
CH
N
0 10 20 30 40 50km
1. Gorges de la Loue
2. Morillon
3. Foncine-le-Bas
4. Haut-de-la-Tour
5. Noirvaux
6. Gorges de l'Areuse
7. Combe-Girard
8. Neuchâtel (n°609)
9. Reuchenette
10. Tramelan
11. Montbautier
12. Graitery
13. Raimeux
14. Vabenau
15. Banné
16. Bure (n°5)

Fig. 10. Correlations based on microfacies evolution and kaolinite distribution (fraction < 2 µm) at Morillon, Gorges de la Loue (A = Calcaires de Besançon, B = Calcaires et Marnes de Chargey, C = Calcaires à stromatoporidés de Matafelon, D = Calcaires des Fins, E = Calcaires de la Loue, F = Tidalites d'Arc-sous-Cicon, G = Calcaires et Marnes de Savoyeux), Gorges de l'Areuse (Combe-Garot), Reuchenette and Vabenau. (bar = 10 m.).

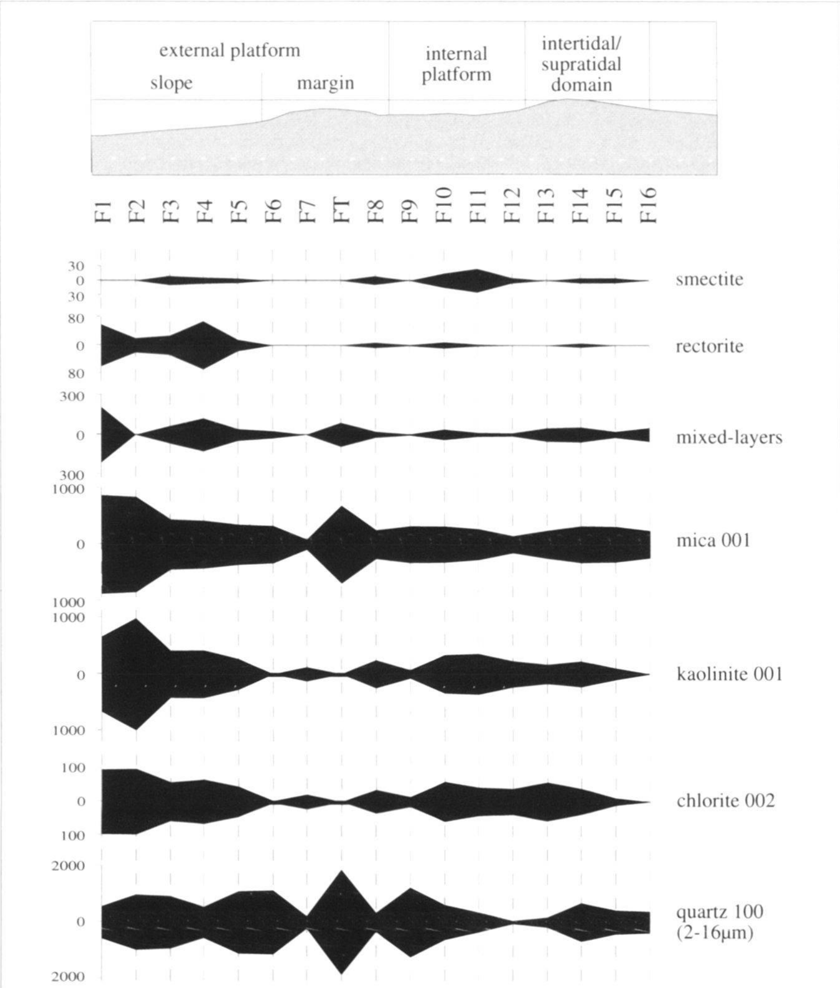


Fig. 11. Distribution of minerals on the Kimmeridgian shelf.

Kaolinite distribution and correlation

Mineralostratigraphic correlations are based on variations of the kaolinite content. Kaolinite distribution profiles present significant analogies in the different sections (Fig. 10). Correlations based on kaolinite seem to confirm the proposed microfacies correlations. The discontinuity D1 is underlined by a sharp decrease in kaolinite content.

Kaolinite content appears to be independent from the different lithologies and depositional environments which is a strong argument for its detrital origin. The variations observed in the kaolinite pattern reflect therefore variations of the detrital supply.

The variations in kaolinite content might reflect climatic changes. An analysis of stable isotopes (bulk rock, ETH Zürich) of samples of the Gorges de la Loue section supports this hypothesis. Values of $\delta^{13}C$ are generally between 1 and 2.5‰ (PDB), $\delta^{18}O$ between –4 and –2‰ (PDB). A major isotopic negative excursion is measured in both $\delta^{13}C$ and $\delta^{18}O$ (‰PDB) at discontinuity D1 (Fig. 14). These shifts are not linked with great changes in microfacies or mineralogical composition.

Diagenetic alteration of the series, due to recristallization of carbonate in the presence of meteoric water may be indicated by a covariance of carbon and oxygen isotopes (Jenkyns & Clayton, 1986). When plotted as $\delta^{13}C$–$\delta^{18}O$ graph, the carbon and oxygen isotope data show no evident covariance (nb. of samples = 38, $r^2 = 0.312$). This suggests that the isotopic composition of the analysed sediments has not been significantly altered by diagenesis. Stable isotopes can thus provide another tool for correlations in the Upper Jurassic.

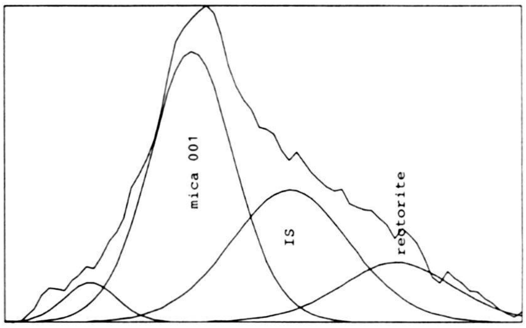
Correlations, sequence stratigraphy and cyclostratigraphy

Correlations

The different profiles are correlated by using variations of microfacies and of kaolinite content. Moreover, short distance correlations have been established, using the joint appearance of the dasycladacean algae *Clypeina jurassica* and *Campbelli-*

FN: MON8G2.NI ID: MONTBEAUTIER 8 <2 GLYCOLE SCINTAG/USA
DATE: 08/31/93 TIME: 06: 33 PT: 1.80000 STEP: 0.03000 WL: 1.54060

PK#	2-THETA	PK-HGT	FWHM
1	8.7926	437	0.397
2	9.1833	214	0.555
3	9.6087	96	0.529
4	8.3845	64	0.249



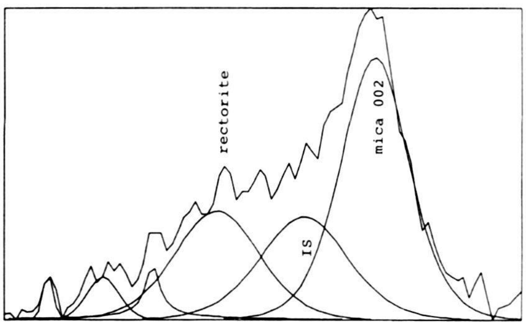
Iteration 15 Error 9.68

Line	Two-theta	sigma	Peak (CPS)	sigma	ESD Fwhm	ESD Exp	Area (CPM)
1	8.7926	0.0348	437.10	149.91	0.0594	5.44	11317.86
2	9.1833	0.1116	213.73	92.44	0.4196	6.51	7736.69
3	8.3845	0.0324	64.13	15.40	0.0402	17.63	1040.70
4	9.6087	0.1996	96.50	112.38	0.1474	9.53	3402.46

Fig. 12. X-ray diffraction pattern presenting reflections of mica 001, mixed-layers (IS) and rectorite near 10°2θ CuKα$_1$.

FN: MON8G2.NI ID: MONTBEAUTIER 8 <2 GLYCOLE SCINTAG/USA
DATE: 08/31/93 TIME: 06: 33 PT: 1.80000 STEP: 0.03000 WL: 1.54060

PK#	2-THETA	PK-HGT	FWHM
1	17.6933	231	0.414
2	16.8799	95	0.515
3	17.3277	90	0.533
4	16.5479	49	0.092
5	16.0081	41	0.060
6	16.2925	37	0.194



Iteration 15 Error 18.41

Line	Two-theta	sigma	Peak (CPS)	sigma	ESD Fwhm	ESD Exp	Area (CPM)
1	17.6933	0.0690	231.12	170.96	0.0924	3.30	6416.18
2	17.3277	0.2365	90.44	131.49	1.1111	23.74	3202.42
3	16.8799	0.2462	95.39	117.00	0.3977	15.71	3237.62
4	16.2925	0.0284	37.47	13.09	0.0705	46.09	473.10
5	16.0081	0.0093	40.73	12.10	0.0249	69.06	155.79
6	16.5479	0.0166	48.68	24.75	0.1226	0.41	681.76

Fig. 13. X-ray diffraction pattern presenting reflections of mica 002, mixed-layers (IS) and rectorite between 16–17.7°2θ CuKα$_1$.

ella striata, as proposed by Strohmenger et al. (1991). Two major discontinuities are correlatable over the whole studied area: D1 and D2.

D1 is located at Gorges de la Loue at the top of the Calcaires de la Loue and marked by a strong erosion (Fig. 9). The top of the Calcaires de la Loue is dated as Acanthicum Zone by Chevallier (1989). This major discontinuity is recognized at Morillon, Reuchenette and Vabenau (below the Banné Marls) and in all other sections and drillholes covering this stratigraphic interval. The D1 discontinuity is generally marked by the absence of kaolinite or a low kaolinite content.

The D2 discontinuity is located a few meters below the lithostratigraphic boundary ("Banc à Nérinées" in the Gorges de l'Areuse or "*Exogyra virgula* Marls" at Reuchenette) between "Kimmeridgian" and "Portlandian", just below a bed enriched in *Cladocoropsis mirabilis* Felix. This discontinuity is recognized in all profiles and drillholes. For Meyer (1994) the Banc à Nérinées near Solothurn is to be placed in the Autissiodiorensis Zone, whereas the Virgula Beds of Alle are rather to be placed in the preceding Eudoxus Zone Gygi (1995).

Tentative sequence stratigraphy and cyclostratigraphy

A tentative interpretation of the successions in terms of sequence stratigraphy, as defined by Vail (1977, 1987), Haq (1991) has been carried out. Sequences are made up by three

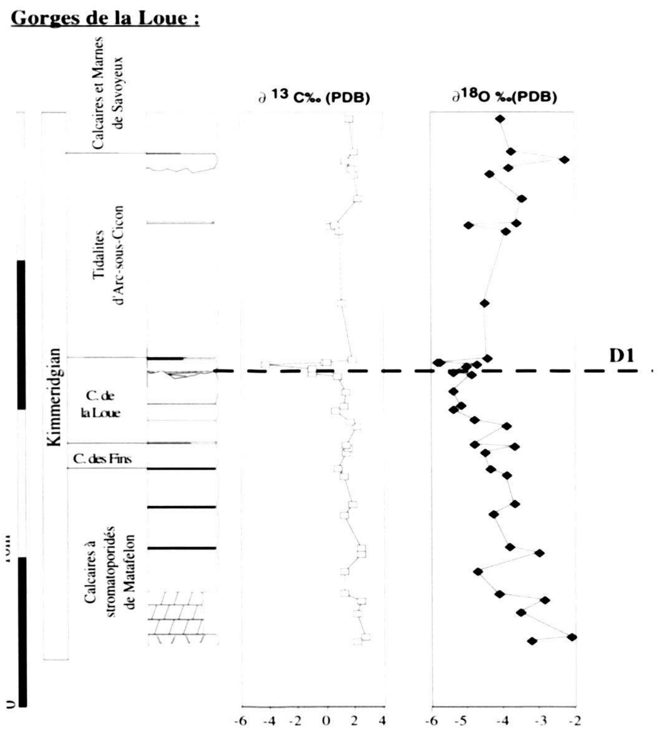


Fig. 14. Gorges de la Loue, $\delta^{13}C$ (‰ PDB) and $\delta^{18}O$ (‰ PDB) variations. Note important shift above major discontinuity D1.

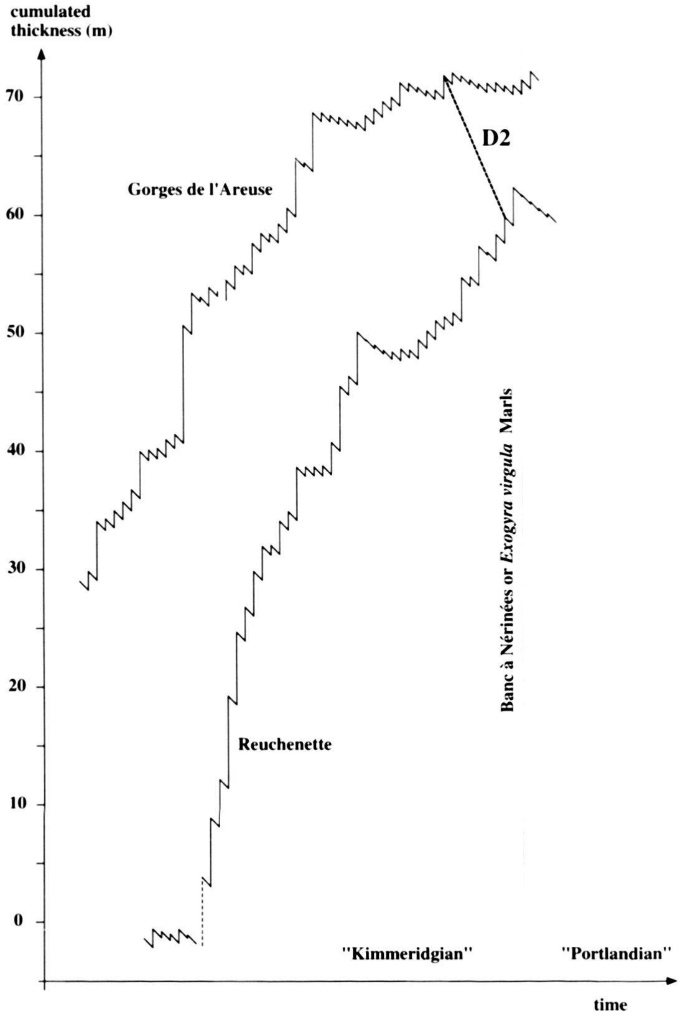


Fig. 15. Comparison of the Fischer-plots representing the upper part of the series at Reuchenette and Gorges de l'Areuse.

kinds of systems tracts: lowstand systems tracts, transgressive systems tracts and highstand systems tracts. But on the Kimmeridgian shelf, sequences sensu Vail (1977, 1987), Haq (1991) and Arnaud & Arnaud-Vanneau (1994) are never complete due to emersion and erosion. Lowstand systems tracts are absent and transgressive systems tracts are rarely represented.

The two major discontinuities (D1 and D2) delimit a sequence sensu Vail. D1 is well marked by karstification underlying a pebbly graded limestone and marly sediments representing mixed-facies in the Gorges de la Loue section. This level probably represents a transgressive systems tract. Otherwise, the deposits between the two major discontinuities (D1 and D2) correspond mainly to a highstand systems tract, but the limit between the transgressive systems tract and the following highstand systems tract is not easily recognizable. In conclusion, application of sequence stratigraphy is very difficult in the sense that the identification of sedimentary bodies in terms of transgressive system tracts, highstand desposits etc. is often impossible. Nevertheless, two major discontinuities are well recognizable and very helpful in establishing regional correlations.

Goldhammer (1987) and Goldhammer et al. (1987) use Fischer-plots (cycle thickness diagram, Fischer, 1964) to correlate series in the Italian Triassic. They recognize eustatic fluctuations of the sea-level corresponding to Milankovitch (1941) cycles. Cycle thickness diagrams have been constructed (Fig. 15), assuming invariant cycle period and subsidence rate (average cycle thickness/period), by plotting the thickness and subsidence of successive cycles versus time. In constructing such diagrams, the thickness of a long and supposedly continuous sequence of cycles is divided by sequence duration to arrive at a long-term rate of regional subsidence. Total duration is then evenly shared out among all cycles. The thickness of each cycle records the amount of accommodation space that is filled during cycle deposition. Cycle thickness less subsidence should reflect changes in the rate of accommodation space creation. If the regional subsidence rate is constant, then such long-term changes could reflect global eustasy. Drumond & Wilkinson (1993) doubt of the liability of this method because the sedimentation is considered as continuous and erosion or compaction of the series are not taken in account. Nevertheless, a tentative comparison between Gorges de l'Areuse and Reu-

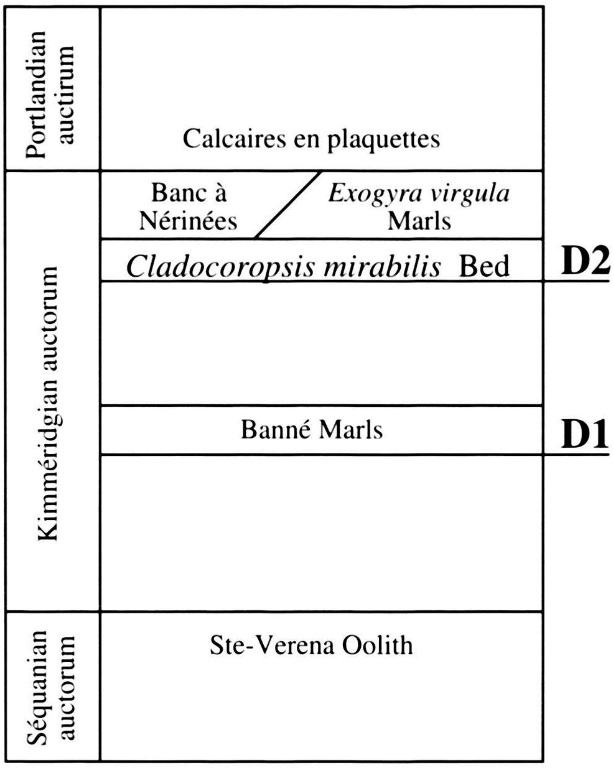


Fig. 16. Recognizable Kimmeridgian formations and discontinuities.

chenette's upper parts of the sections was made. The two sections show a cyclic repetition of emersive layers between the two major discontinuities D1 and D2. Both Fischer-plots are very similar (Fig. 15) and some peaks could be correlated. This confirms the correlation based on microfacies and kaolinite distribution. However, without biochronological data, all these correlations remain hypothetical. Note that the general aspect of the Fischer-plot curve is very similar to the Exxon curve (Vail et al., 1987) supporting the assumption that the cyclicity is due to eustasy.

Conclusions

The Reuchenette Formation was introduced by Thalmann (1966) to replace the Kimmeridgian auctorum without changing its boundaries. This formation is, however, only defined by its boundaries. Lithology and its fossil content are not characteristic. The Reuchenette Formation is, thus, difficult to map and does not seem to be a good type-formation for the Swiss Jura mountains.

The same is true for the formations established by Bernier (1984) and Chevallier (1989) in the French Jura Mountains. Many of them are not recognizable by their lithology or fossil content. Moreover, their boundaries are often not obvious. Only some of these formations are recognizable over short distances, thus allowing lithostratigraphic correlations: Ste-Verena Oolith, Banné Marls, Banc à Nérinées and *Exogyra virgula* Marls and the Banc à *Cladocoropsis mirabilis* Felix. The latter is located just below the classical lithostratigraphic markers of the Kimmeridgian auct.-Portlandian auct. limit (Fig. 16).

The correlations made here are mainly the result of field observations, microfacies analyses and the kaolinite distribution.

Two major discontinuities corresponding to sequence boundaries have been recognized in Kimmeridgian strata enabling us to propose chronostratigraphic correlations for the studied area. D1 is located in the Acanthicum Zone (Chevallier, 1989, Gygi 1995), D2 corresponds to SB140 determined by Strohmenger et al. (1991) located in the Autissiodiorensis Zone (Meyer, 1994, Gygi 1995).

Therefore it seems more convenient to come back to the ancient authors' nomenclature, using a "Kimmeridgian" *(sensu gallico)*, even if this is only approximate in the chronostratigraphic sense.

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