Tectono-biosedimentary recordings at the Lias-Dogger transition: example of the Quercy carbonate platform (Aquitaine Basin, France)

Article *in* Bulletin de la Societe Geologique de France · July 2007

DOI: 10.2113/gssgfbull.178.4.275

Carine Lézin
Paul Sabatier University - Toulouse III

Jacques Rey
French National Centre for Scientific Research

Pelissie Thierry

Bull. Soc. géol. Fr., 2007, t. 178, n° 4, pp. 275-291

Tectono-biosedimentary recordings at the Lias-Dogger transition: example of the Quercy carbonate platform (Aquitaine Basin, France)

CARINE LEZIN[1], JACQUES REY[1], PHILIPPE FAURE[2], RENÉ CUBAYNES[3], THIERRY PELISSIE[1], CHRISTOPHE DURLET[4] and JEAN-FRANÇOIS DECONINCK[4]

Key words. – Toarcian, Aalenian, Carbonate platform, Sedimentation, Tectonics, Quercy, France.

Abstract. – On the eastern edge of the Aquitaine Basin, the Lias-Dogger transition and the events, which occurred during this time interval are studied in the Quercy sedimentary basin. Stratigraphic correlations are proposed using a biochronological calibration based on the determination of numerous ammonites and brachiopods. Facies analyses using statistical processing integrate the presence of faults and tectonic compartments and lead to reconstruction of palaeoenvironments in space and time. The paper includes the description of system tracts following Haq *et al.* [1987] and Vail *et al.* [1991], and twelve palaeogeographic maps of the area studied. The objectives are to distinguish the various allocyclic and autocyclic factors controlling sedimentation and to show the impact of the Mid-Cimmerian tectonic event on the evolution of the basin.

Enregistrements tectono-biosédimentaires au passage Lias-Dogger : exemple de la plate-forme carbonatée du Quercy (bassin d'Aquitaine, France)

Mots-clés. – Toarcien, Aalénien, Plate-forme carbonatée, Sédimentation, Tectonique, Quercy, France.

Résumé. – Le Quercy, sous-bassin sédimentaire situé sur la bordure orientale du Bassin aquitain, constitue l'une des rares plates-formes intracratoniques du Nord-Ouest de la Téthys à avoir enregistré une sédimentation néritique relativement continue au passage Lias-Dogger.

A partir d'un calage biochronologique fondé sur la détermination de nombreuses ammonites et brachiopodes, et d'une analyse fine des faciès, des corrélations stratigraphiques sont proposées. Intégrant la présence de failles et de compartiments, tectoniques, cette analyse permet une reconstitution des variations spatio-temporelles des paléoenvironnements, traduite par l'édition de 12 cartes paléogéographiques et par la description de séquences de dépôt de 3e ordre sensu Haq *et al.* [1987] et Vail *et al.* [1991]. L'objectif est de faire la part entre les différents facteurs allocycliques et autocycliques qui contrôlent la sédimentation et de montrer l'impact de la phase tectonique dite "mi-cimmérien" [e.g. Graciansky et Jacquin, 2003] sur l'évolution du bassin.

Du Toarcien supérieur (zone à Pseudoradiosa) au Bajocien, la sédimentation et la géométrie des dépôts apparaissent dans le Quercy sous contrôle tectonique continu. Le maximum d'activité tectonique, qui s'exprime par la surrection des seuils périphériques au bassin et induit son semi-isolement, est daté du sommet de la zone à Opalinum et de la base de la zone à Murchisonae. Cet événement pourrait être rattaché à l'événement "mid-cimmérien". Résultant des effets conjugués de l'accélération du rifting téthysien, du rifting de la mer du Nord et de l'ouverture de l'Atlantique central, il a des conséquences modérées sur l'évolution paléogéographique, comme en témoigne l'enregistrement continu de la sédimentation.

A la différence des autres bassins, ce maximum d'activité tectonique est décalé dans le temps par rapport au maximum de régression du 2nd ordre qui est daté de la zone à Concavum ou de la base du Bajocien.

A l'échelle du troisième ordre, 5 séquences de dépôt *sensu* Haq *et al.* [1987] et Vail *et al.* [1991] ont été identifiées. La contribution respective des variations eustatiques et de la tectonique régionale sur les variations du niveau marin relatif n'a pas pu être évaluée.

D'un point de vue paléoenvironnemental, il apparaît que de la transition entre le Lias et le Dogger n'est ici marquée par aucun changement biosédimentaire qui pourrait être significatif en termes de variations climatiques majeures.

1. Laboratoire des Mécanismes de Transfert en Géologie, Univ. Toulouse, CNRS, IRD, OMP, 14 avenue Edouard Belin, 31400 Toulouse, France. E.mail: lezin@lmtg.obs-mip.fr
2. 3, rue Corne Basse, 81100 Castres, France
3. 59, chemin Fourestole, 81990 Cambon, France
4. UMR CNRS 5561 "Biogéosciences", Université de Bourgogne, 6 Bd Gabriel, 21000 Dijon, France
Manuscrit déposé le 19 octobre 2005; accepté après révision le 13 décembre 2006.

INTRODUCTION

In western European and Tethyan basins, Upper Toarcian-Aalenian deposits are generally included in a regressive second-order cycle, which begins in the middle Toarcian and ends during the Aalenian [e. g. Rioult *et al.,* 1991; de Graciansky *et al.,* 1993; Razin *et al.*, 1996; Hardenbol *et al.*, 1998; Jacquin *et al.*, 1998; O'Dogherty *et al.*, 2000; Floquet *et al.*, 2000; Aurell *et al.*, 2003]. The regressive trend, often expressed by the development of carbonate platforms over the Toarcian marly deposits, is linked with the break-up of Pangea, which includes opening of the Central Atlantic, rifting of the Tethys and doming of the North Sea. In France, this period is characterised by accentuation of palaeotopography, erosions and reactivation of ancient faults [Jacquin *et al.*, 1998; Robin, 1997; Guillocheau *et al.,* 2000; de Graciansky *et al.*, 2003; Robin *et al.*, 2003; Thiry-Bastien, 2002; Durlet *et al.*, 1997; Durlet and Thierry, 1999; Quesne *et al.*, 2000]. This period also coincides with uplifts recorded in Normandy (Lower Aalenian and Lower Bajocian) [Rioult *et al.*, 1991] and the North Sea [Jacquin *et al.*, 1998]. On most intracratonic platforms, the result is a discontinuous and poor sedimentary record of tectonic and biosedimentary events characterising the maximum of regression at the 2nd order scale *sensu* Hardenbol *et al.* [1998].

The Quercy area, located on the northeastern border of the Aquitaine Basin, is one of the rare French platforms where sedimentation was relatively continuous from Upper Toarcian to Early Bajocian. The objective of the paper is therefore to decipher the sedimentary record including tectonic and biosedimentary events during the regressive evolution.

The study includes: facies analysis integrating statistical treatments [Lézin *et al.*, 2000]; stratigraphic correlations based on biochronological data (ammonites and brachiopods); drawing up of palaeogeographic charts integrating the presence of faults and tectonic blocks poorly described so far for their synsedimentary influence during the Jurassic; a reconstruction of space-time palaeoenvironmental variations to identify depositional sequences at the 3rd order scale *sensu* Haq *et al.* [1987] and Vail *et al.* [1991].

At the end of this sedimentological, palaeogeographic and sequential synthesis, an examination of the different allocyclic factors that may have driven the sedimentation in this region during the Lias-Dogger transition is proposed. We integrate the results of mineralogical (clay minerals) and palynological analyses. By comparison with other, near or distant sedimentary basins, the chronology of the different tectonic, eustatic, and possibly climatic events is discussed.

GEOLOGICAL, CHRONOLOGICAL SETTINGS AND CORRELATIONS (fig. 1)

The polygonal Quercy sub-basin (fig. 1), located on the northeastern edge of the Aquitaine basin, is bordered by the Villefranche-de-Rouergue fault (east) and by the West-Quercy lineament (west). The series, ranging in age from the Upper Toarcian to the Lower Bajocian (fig. 2), crops out on the eastern border in a narrow belt of N-S general orientation. Sixty outcrops were studied (fig. 1). In the Quercy Basin, the precise chronological setting of Lias, and particularly that of Upper Toarcian, has been established by Cubaynes and Fauré [1981]. Twenty-six ammonite horizons have been recognized. Some recent data make possible the local biostratigraphic scale to be improved in 7 biozones on the basis of the ammonite fauna, with the exception of the last, for which identification relies on determinations of brachiopods [Lézin *et al.*, 1997; Fauré *et al.*, 2000]. This biozonation is in agreement with the standard scale defined by Elmi *et al.* [1997] and Contini *et al.* [1997] respectively for Toarcian and Aalenian stages.

The Lias-Dogger transition corresponds to the Aalensis, Opalinum and Murchisonae zones.

In Aalensis Zone, new local bio-horizons have been defined [Fauré *et al.*, 2000] (fig. 3): the Fluens, Crinita and Lugdunensis-Burtonensis bio-horizons. This zone is also characterised by the brachiopod index: *Zeilleria lycetti* (DAVIDSON) and *Lobothyris haresfieldensis* (DAVIDSON). The presence of *Loboidothyris* sp. points out the transition from the Aalensis zone to the Opalinum zone. *Homoeorhynchia cynocephala*, (RICHARD) – that appears at the top of the Pseudoradiosa zone – abounds there.

In sub-Mediterranean and sub-boreal provinces [Contini *et al.*, 1997], the Opalinum Zone includes 2 subzones (Opalinum and Bifidatum), but in Quercy, only the first one has been recognised (the absence of biostratigraphic markers does not allow the second sub-zone to be identified).

The lower part of the Murchisonae Zone (Haugi and Murchisonae subzones) has been defined by the presence of brachiopods: *Sphaeroidothyris silicea* ALMÉRAS and MOULAN, *Stroudithyris pisolithica* (BUCKMAN), *Monsardithyris trilineata* juv. (YOUNG and BIRD), *Pseudoglossothyris brebissoni* (DESLONGCHAMPS).

On the basis of these precise biochronological data, a N-S correlation scheme is established (fig. 4). This highlights the sedimentary hiatuses and the diachronism of some discontinuities or facies breaks and confirms the subdivision of the Quercy Basin into two morphostructural units:

– a southern unit that subsides progressively southward;

– a northern unit that subsides gradually in the direction of the Autoire area (SE).

Each of these is subdivided into blocks that control the depositional pattern of the sediments.

PALAEOENVIRONMENTAL EVOLUTION AND SEQUENCE STRATIGRAPHY

Sixteen facies associations are distinguished from the analysis of samples coming from about sixty outcrops. Their main features are presented in tables I and II.

The facies associations 1 to 7 (tab. I) are characterised by the presence of both benthic and pelagic faunas (ammonites, belemnites and hyaline benthonic foraminifers, Nodosariidae). These facies associations spread over the lower offshore and the shoreface of an open platform.

In the Middle Aalenian, facies F8 to F12 appear while facies F1 to F7 disappear. The facies associations 8 to 12 (tab. II) are mostly characterised by exclusively benthic faunas, a change of foraminifer assemblages (appearance of *Verneuillinoides*, *Planiinvoluta* sp., *Ophthalmidium* sp.), development of dasycladals and the absence of pelagic faunas and sedimentary structures. Palaeoenvironmental settings

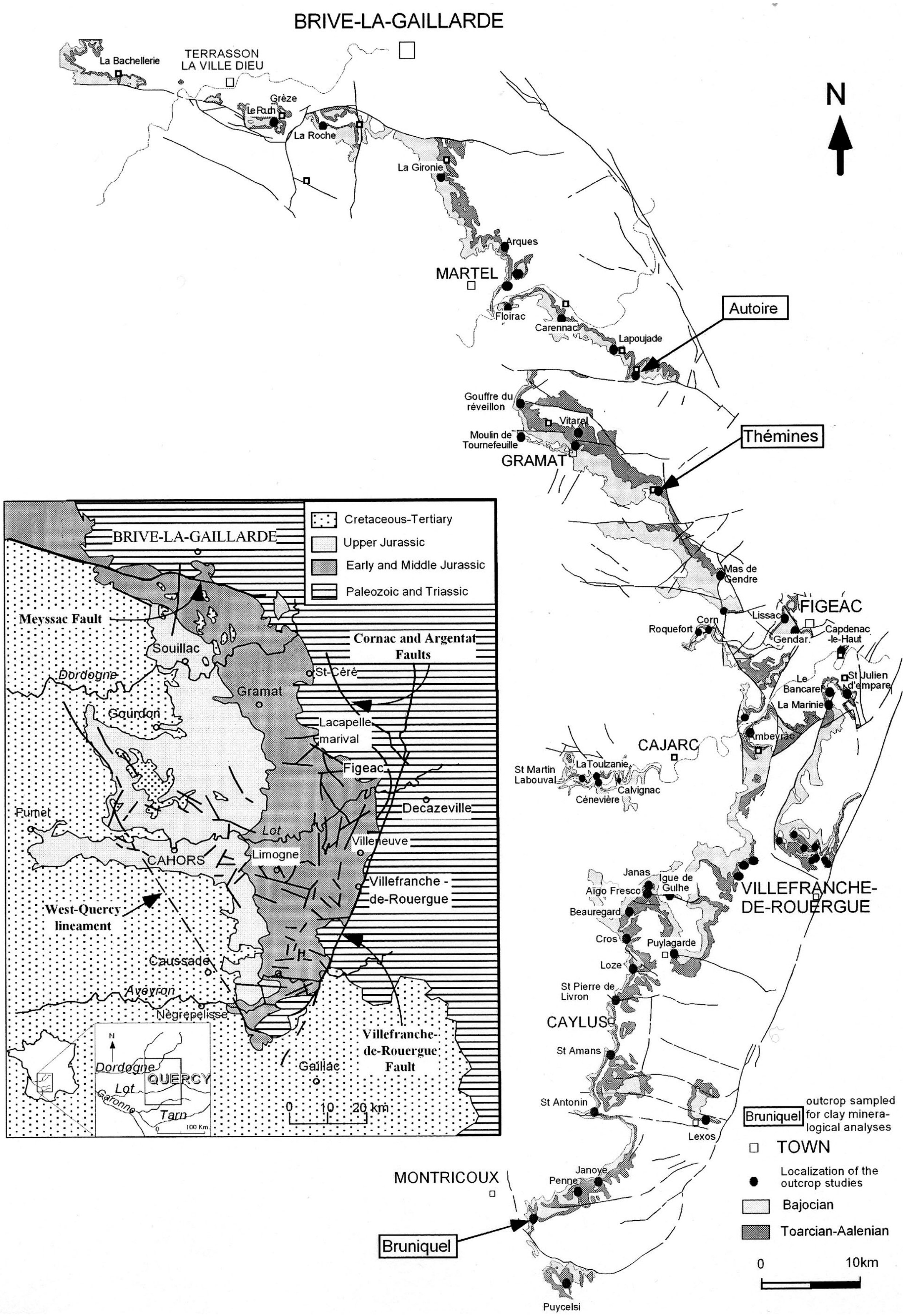

FIG. 1. – Geographical, geological and tectonic map of the area studied.
FIG. 1. – *Cadre géographique, géologique et structural.*

TABLE. I. – Upper Toarcian-Early Aalenian facies description and paleoenvironmental interpretation.
TABL. I. – *Principales caractéristiques des faciès du Toarcien supérieur–Aalénien inférieur et interprétation paléoenvironnementale.*

N° facies	Lithology and texture	Biological, non-biological and hydrodynamic indicators	Palaeoenvironmental interpretation
1	Limestone-marl alternation (mudstone-wackestone). Black laminated (organic matter) marly levels.	– Fragments of bivalves; – small benthic foraminifers (*Ophthalmidium* sp. and *Lenticulina* sp.) ; – spicules of spongiae (locally) ; – endobionts and rare epibionts lamellibranchiata (punctually *Gryphaea sublobata*); – ammonites and brachiopods; – 5% angular grains of quartz (silts). Low density and weak diversity of the fauna: unfavourable environment for the development of a varied benthic microfauna. Absence of Hydrodynamic indicators	Lower offshore, open platform
2	More or less clayey bioclastic limestones.	Lamellibranchiata, echinoderms and annelida fragments. Macrofauna: abundant brachiopods (*Zeilleria cf. lycetti*, *Homoeorhynchia cynocephala* and *Lobothyris haresfieldensis*), ammonites and endobiont - epibiont bivalves. Abundant indeterminable bioturbations.	Lower offshore – upper offshore transition, open platform
3a	Clayey limestones ferruginous grains.	Ferruginous ooids [α et γ ooliths (Purser, 1980)],quartz grains, fragments of ferruginous nodosariids, ammonites and bivalves and echinoderms. The binder is argillaceous, ferruginous and locally dolomitic. Sedimentary structures: oblique stratifications	Distal upper offshore, open platform
3b	Clayey limestones of brown colour.	Ferruginous ooliths and ghosts of ooïds (α and γ), heterometric and heteromorphic, compacted (lenticular shape) and allochthonous (rounded). The binder is micritic and locally dolomicrosparitic. Absence of hydrodynamic indicators	Lower offshore – upper offshore transition, open platform
4	Limestones with rounded echinoderm fragments	One distinguishes all the facies of transition between packstones-grainstones to accumulation of microbiofragments of echinoderms and the biosparite grainstones to accumulation of fragments of echinoderms. Macrofauna: endobiont and epibiont bivalves Sedimentary structures: distal tempestites storm deposit.	Upper offshore, open platform
5	Limestones, grainstone	The macrofauna is reduced (local presence of *gryphaea sublobata*) or completely absent but rounded echinoderm fragments are abundant. Sedimentary structures: macro-hummocky cross stratification.	Upper offshore - shoreface, open platform
6	Limestone, grainstone with syntaxial and drusic cements	Accumulation of ossicles with ferruginous encrustings associated with some bivalve fragments, abundant extraclasts (mud ball), and rare ferruginous ooliths. Sedimentary structures: cross bedding, three dimensional sinous-crested ripples and sigmoid stratifications.	Shoreface (influence of tidal currents in the infratidal zone), open platform
7	Limestones (packstone-grainstone) to bioclastes in course of micritization:	– Echinoderms (ossicles) and lamellibranchiata fragments; – rare ammonites. The micritization is due to a relatively intense perforation, presumably of plant origin. It necessarily implies a low rate of sedimentation. Sedimentary structures: tempestites	Shoreface, open platform. In the present, refilling of perforations occurs only in warm seas between 0 and 10 m deep [Purser, 1980]. A variant of this facies (without tempestite and with oncoids) could deposit in inner bar

extend from the circalittoral zone to the mediolittotal zone on a protected platform [Lézin *et al.*, 2000].

Twelve palaeoenvironmental charts are proposed. Each corresponds to a system tract in a time slot that varies between one or two standard ammonite horizons in the Upper Toarcian and a part of a zone in the Aalenian. These system tracts are integrated in 6 depositional sequences, SD1 to SD6.

The Toarcian-Aalenian evolution of the Quercy Basin can be subdivided into 11 main steps.

TABLE. II. – Middle – Upper Aalenian facies description and paleoenvironmental interpretation.
TABL.II. – *Principales caractéristiques des faciès de l'Aalénien moyen et supérieur et interprétation paléoenvironnementale.*

N° facies	Lithology and texture	Biological, non-biological and hydrodynamic indicators	Palaeoenvironmental interpretation
8a	Clayey limestones and marls	Oncoids of pluricentimetric diameter (5-6 cm). Encrusting organisms: *Nubecularia reicheli*, serpula and bryozoa. No hydrodynamic indicator	lower infralittoral, protected platform
8b	Grey more or less clayey limestones (wackestone-packstone) with abundant oncoids	Oncoids (encrusting organisms: *Nubecularia reicheli*) of infracentimetric size (2 mm to 2 cm). Their shape depends in the shape of the bioclast that constitutes the nucleus. Encrusted elements: fragments of echinoderm and of lamellibranchiata, small gastropods and benthic foraminifers (nodosariidae). Other allochems: benthic foraminifers [*Ophthalmidium* sp., *Planiinvoluta* sp., *Glomospira* sp. and nodosariidae (Lenticulina sp.)], peloids, dasycladals (*Holosporella* sp.), spicules of spongiae (locally), rare scleritis of holoturian, lamellibranchiata and echinoderm fragments. Macrofauna: rare brachiopods (the majority juvenile shapes). No hydrodynamic indication	Infralittoral, protected platform. Nowadays nubecularids abound in the shallow environments of warm seas. Rat [1966] explains the development of these encrusting foraminifers by the extension of the clear warm waters and by the abundance of the organo-detrital sandy floor. The association of the nubecularids with dasycladal fragments suggests their proliferation within the photic zone in a calm, shallow depositional environment (protected) [30 to 40 m, Branger [1989]].
9a	Limestone-marl alternation (wackestones to packstones locally).	– Microbioclasts (echinoderm fragments); – peloids with diffuse and irregular shape; – little varied (ubiquists species) and reduced population of ostracodes and of nodosariidae. No hydrodynamic indication	Circalittoral - lower infralittoral, protected platform
9b	Limestones (biopelmicrite or biopelsparite packstone - grainstone).	– Abundant peloids of regular and hardened shape; – numerous benthic foraminifers (verneuilinoïds, *Planiinvoluta* sp., *Ophthalmidium* sp); - spicules of spongiae and rare oncoids. No hydrodynamic indication	Limit between the infralittoral and intertidal zones, protected platform. Purser [1980] indicates that the hardening of the pellets takes place in a shallow environment (< 5 m).
10	Limestones (packstone-grainstone)	Benthic foraminifers (verneuilinoids, *Planiinvoluta* sp.., *Ophthalmidium* sp.), locally isolated polypiers, peloids, oncoids, bahamites and grapestones. No hydrodynamic indication	Upper infralittoral zone, in inner oolithic bar [Cros, 1979]. protected platform
11	Limestones with bahamites	– Bahamites whose size varies between 500 µm and 2 mm. The nucleus is composed of lamellibranchiata and echinoderm fragments, benthic foraminifers. No hydrodynamic indication	Limit between the infralittoral and intertidal zones (inner oolitic bar) [Cros, 1979; Purser, 1983; Strasser, 1986]. protected platform
12a	Dolomicrite	Dolomitic facies (microcrystalline dolomite). "ghosts" of oncoids, echinoderms and peloids. No hydrodynamic indication	Infralittoral, protected platform.
12b	Yellow, pink or orange recrystallized limestones	The calcite crystals are micro in macrocrystallines (poecilitic calcite). Ghosts of dolomite and bioclasts (some silicified), geoids filled with quartz and calcite and quartz grains. No hydrodynamic indication	Infralittoral-mediolittoral, protected platform
12c	Rust recrystallized limestones	Ghosts of ooïds (ooliths with sparitic refilling and/or ghosts of rounded echinoderm fragments), geoids filled with quartz and calcite, and macrocrystalline calcite. No hydrodynamic indicators	Infralittoral-mediolittoral, protected platform

Top of the Fallaciosum subzone (Thouarsense zone, upper Toarcian): filling phase and first building-up of the carbonate platform

On the Quercy platform, the top of the Thouarsense zone (fig. 5a) is expressed by a double limestone bed recognised on all outcrops and boreholes [Cubaynes, 1986]. Facies analysis shows a relative uniformity of palaeoenvironmental conditions, suggesting a relatively flat palaeotopography, where it is not even possible to distinguish a polarity in the organisation of the deposits. This double bed encloses the filling phase (HST SD0) beginning at the Thouarsense horizon during the Late Toarcian [Cubaynes, 1986]. In most of the sites studied, a hardground occurs at the top of the

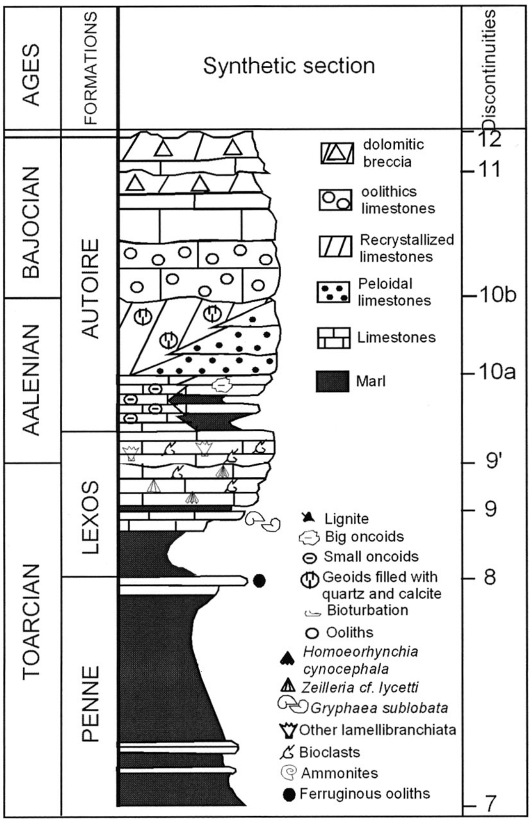

FIG. 2. – Synthetic sections of the Lexos and Autoire formations dating from the Upper Toarcian and Aalenian in the Quercy area.
FIG. 2. – *Le Toarcien supérieur et l'Aalénien dans le Quercy : unités lithostratigraphiques, évolution sédimentaires et principales discontinuités.*

double bed dated to the Fallaciosum horizon. This discontinuity, probably formed in an upper offshore submarine environment, includes both the sequence boundary and the transgressive surface of SD1.

Dispansum zone: deepening phase and pre-structuring (IT SD1)

Over the whole Quercy area, this interval is characterised by a terrigenous sedimentation (facies 1) in lower offshore environments (fig. 5b). The homogeneous sedimentation (IT SD1) prevents the identification of a coastal zone on the edges of the currently preserved basin from being distinguished. However, some shoals identified by the absence of deposits [for example Thémines area (2), St. Martin-Labouval area (4)] appear locally. No sign of shoreface or backshore deposits or of emersion has been observed on or near these shoals suggesting either non-deposition or submarine erosion. The finely detrital sedimentation develops only in the depressed areas.

Pseudoradiosa zone and Mactra horizon (Mactra subzone, Aalensis zone): New filling phase (HST, SD1)

From the Pseudoradiosa zone (fig. 5c) to the end of the Mactra horizon, sedimentation becomes less uniform. A palaeoenvironmental zonation appears during the early stages of this interval, with depositional environments ranging from lower offshore to upper shoreface. This zonation, without zones of well-marked facies change, is typical of a carbonate ramp slightly tilted toward the east and the southeast. However, three major shoals can be individualised: a northern shoal, the "Gironie shoal (6)", oriented N-S, where carbonate bioproduction predominates; the shoal localised in the St. Martin-Labouval area (central Quercy (4)) marked by the absence of silty marls (hiatus of the Dispansum zone and the Pseudoradiosa zone); and the shoal of Figeac-Capdenac (9), on the eastern border of the central Quercy, pointed out by a hiatus of the summit of the Pseudoradiosa zone and, at its margin, by the occurrence of ferruginous oolites scattered in clayey sediments (facies 3b).

The depressed zones that edge these shoals are located near major accidents: for example between the Padirac and Argentat-Cornac faults in the Autoire area (7). In the Pseudoradiosa zone, filling becomes widespread, with the development of a sedimentation in shallower environments. The latitudinal and longitudinal (in the southern Quercy) zonation of the environments implies the influence of perennial east-west and north-south tectonic structures.

Deposition of the "Assise à gryphées" unit (Mactra horizon) closes this phase of sedimentary filling, which is interrupted by the D.9 discontinuity (sequence boundary and transgressive surface of SD2, fig. 4). On most sections, this limit corresponding to a local softground or hardground indicates a sedimentation break. The sedimentary filling develops during the highstand sea level; the shelf margin wedge is not represented in the Quercy Basin.

Celtica horizon (Mactra subzone, Aalensis zone): new flooding phase of weak amplitude

In the Celtica horizon (fig. 5d), a lower offshore sedimentation characterised by glauconite bearing marly deposits with a minor biodetrital fraction spreads over a large part of the area (facies 1). This more distal sedimentation characterises an increase of the available space for sediment accumulation during the transgressive phase (IT SD2).

On the Gironie shoal, an upper offshore sedimentation develops (facies 4). At the same time, the ferruginous oolites disappear in the Capdenac area and new hiatus zones (without emersion) appear in northern and central Quercy. Their appearance implies a new topographic differentiation, with differential sedimentation, the presence of bypass zones and a new distribution of the shoals. This local structuration is also suggested by diachronous deepening in different part of the basin. On most sections, the maximum flooding is indeed dated to the summit of the Celtica horizon where it is marked by a high concentration of ammonites or ferruginous minerals. In other areas, the change of transgressive/regressive tendency takes place later, during the Lugdunensis horizon (e.g. Gramat section).

Lugdunensis horizon (Ludgdunensis zone and subzone): new phase of filling in two stages (HST, SD2)

From the Lugdunensis horizon (fig. 5e) to the base of the Buckmani horizon, except local deepening, the sedimentation displays a more proximal character than in the Celtica horizon.

The abundance and diversity of brachiopods in some sections (e.g. Thémines, Gramat, La Toulzanie, Saint Pierre de Livron) suggest some particular palaeoenvironmental conditions: hard bedrock, low sedimentation rate, clear and oxygenated waters and weak hydrodynamism permitting oxygenation and the renewal of nutrients [Alméras and Moulan, 1982]. Areas of hiatuses are reduced, which can be explained by a sedimentary filling tendency (HST, SD2) associated with relative increase of the carbonate production and decrease of the detrital supply. Sedimentation becomes progressively homogeneous at the end of the Buckmani horizon and during the Subglabrum horizon (Opalinum zone and subzone, Lower Aalenian, fig. 5f). Bathymetric contrasts are less obvious, and depositional environments range from the upper offshore to the shoreface. Above, an erosional surface occasionally punctuated by ferruginous deposits, indicates the end of the sedimentary filling phase and the end of the Toarcian. In spite of the importance of the hiatus zones (bypass zones and/or eroded zones) and the possible continental origin of the ferruginous deposits, there is no evidence for the existence of an emersion phase at the end of SD2.

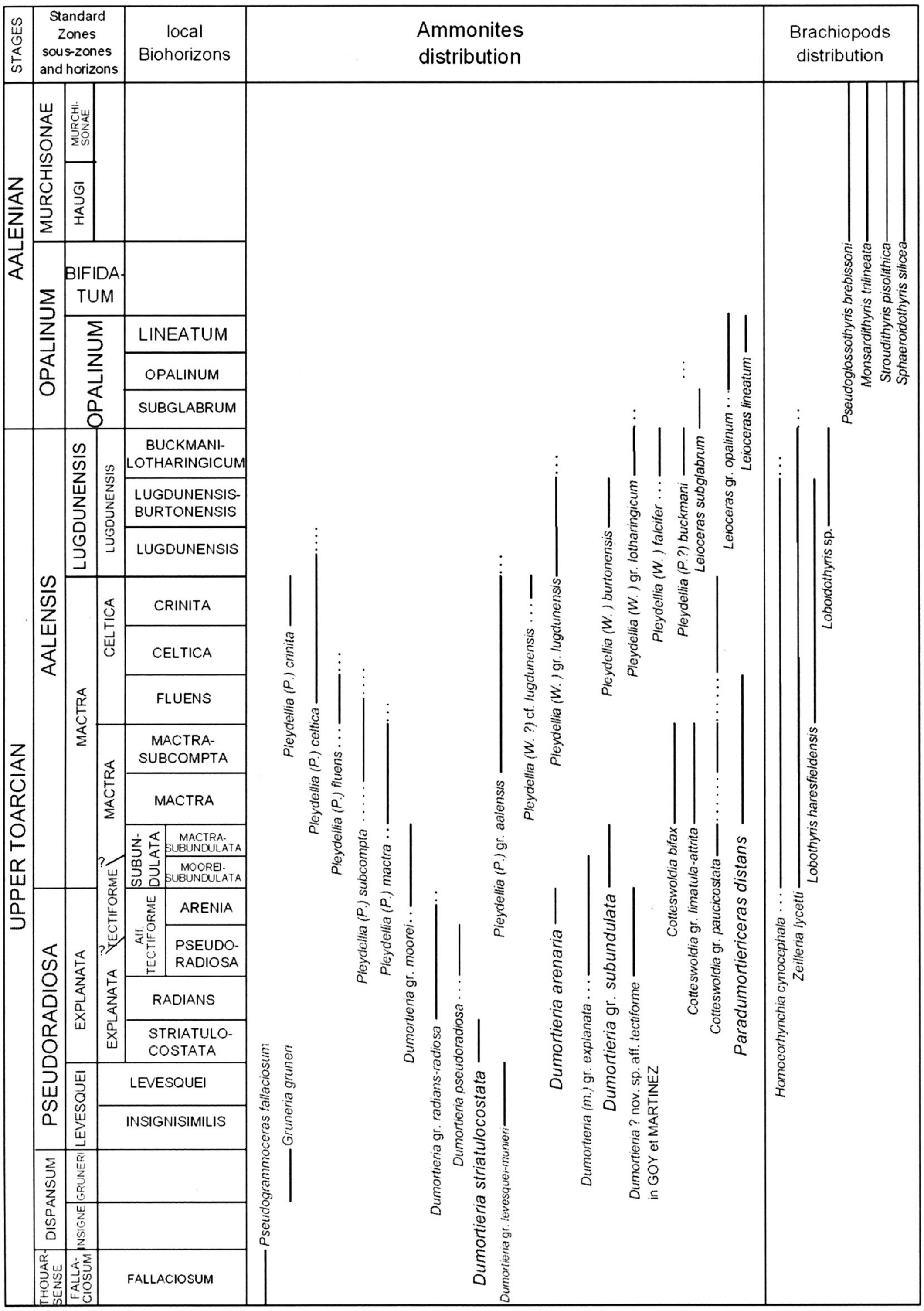

FIG. 3. – Biostratigraphic data from Toarcian to Middle Aalenian in the Quercy area.

FIG. 3. – *Extension verticale des principaux marqueurs biochronologiques du Toarcien supérieur et de l'Aalénien inférieur à moyen du Quercy.*

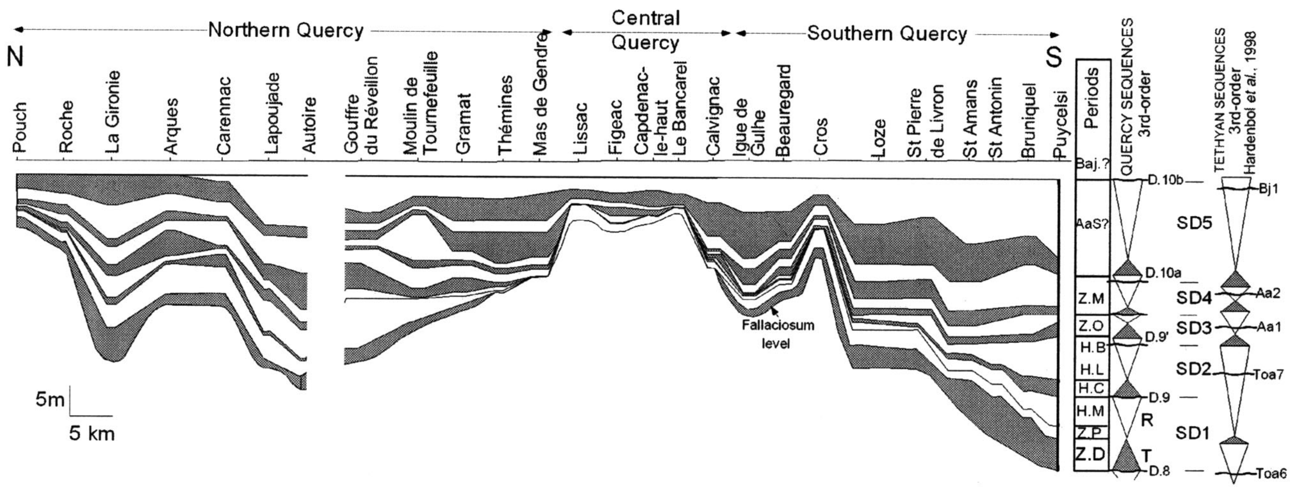

FIG. 4. – Stratigraphic correlations along a North/South transect.
Z.D: Dispansum zone, Z.P: Pseudoradiosa zone, H.M: Mactra horizon, H.C: Celtica horizon, H.L: Lugdunensis horizon, H.B: Buckmani horizon, Z.O: Opalinum Zone, Z.M: Murchisonae Zone, AaS: Upper Aalenian, Baj.: Bajocian, D.10b = discontinuity named 10b, S1: sequence number 1, T: transgression, R: regression.
FIG. 4. – *Corrélations stratigraphiques suivant un transect N-S.*

Early Aalenian (Opalinum subzone): installation of a carbonate platform

From the Early Aalenian (fig. 5g), a carbonate platform develops in a transgressive context. The increase of accommodation (IT, SD3) is characterised by a reduction of the hiatus zones, mainly located in central Quercy, and by a more distal sedimentation than at the end of the Toarcian stage. A new facies characterised by calcarenites with echinoderm debris, partially micritized by fungi or bacteria (facies 7), chiefly appears in southern Quercy.

In the St. Rémy area (10 fig. 5c), the sedimentary polarity changes from the beginning of the Aalenian (fig. 5g). A more proximal sedimentation appears along the Villefranche fault, while westward, the sedimentation becomes more distal. These changes reveal a slowing down or even a subsidence break near the Villefranche-de-Rouergue fault during the basal Aalenian.

Summit of the Lower Aalenian: beginning of installation of a protected platform

At the summit of the Lower Aalenian (fig. 5h), bioclastic bars deposited in inner environments (facies 7) occur progressively in the Quercy area. Sedimentation becomes homogeneous, carbonate deposits develop on the whole platform and the hiatus zones are shortened further to generalized filling (H.S.T., SD4). An unconformity closes this phase of sedimentary filling and constitutes both a sequence boundary and a transgressive surface (SB and ST SD4). It is expressed either by a simple, abrupt lithological change, or by an erosional non-lithified surface, or by one or more hardgrounds. Their diagenetic analysis does not reveal any evidence of emersion. These surfaces became progressively lithified in a marine phreatic environment by high magnesian calcite cements (acicular calcite now recrystallised into inclusion-rich low magnesian calcite) and were probably abraded by the surge in the shoreface zone.

Basis of the Middle Aalenian: the major palaeogeographic modification

At the beginning of the Middle Aalenian (fig. 6a), infralittoral protected platform sedimentation took place over the whole Quercy, with the deposit of oncoids-rich clayey limestone (biomicrite wackestone, facies 8b). Some areas of land subsidence that had disappeared during the Lower Aalenian reappeared (for example east of the Causse de Martel). Hiatus zones are rare. We recognized only one shoal located to the east of Central Quercy. The environmental context of the Quercy Basin changed: a protected carbonate platform occurred at the top of the Opalinum zone and mainly at the base of the Murchisonae zone. This palaeogeographical change implies a reduction of connections with the open marine zone but it occurred during a flooding phase of the Quercy platform. This transgressive tendency is expressed in nearly all sites by an increase in the clay and a predominance of wackestone/mudstone textures. The maximum flooding (MFS, SD4) is marked either by a ferruginous layer, or by brachiopods concentrations, or by a centimetric horizon of concentration in crinoids and ammonites revealing a brief episode of opening toward offshore environments.

The Middle Aalenian summit: filling phase of the protected platform

At the end of Middle Aalenian (fig. 6b), inner oolitic bar deposits are observed on the western border of the basin. In the rest of the domain, some biopelmicrites (packstone to grainstone) with abundant benthic foraminifers appear abruptly. Dolomitization, which probably results from an early process (microcrystalline dolomite), becomes more intense at the summit of some sections. The appearance of this infralittoral to mediolittoral facies implies a new filling trend (HST, SD4). The maximum of regression for this cycle (sequence boundary and transgressive surface, SD5) is marked either by an erosive surface (Bruniquel) or by a marly layer.

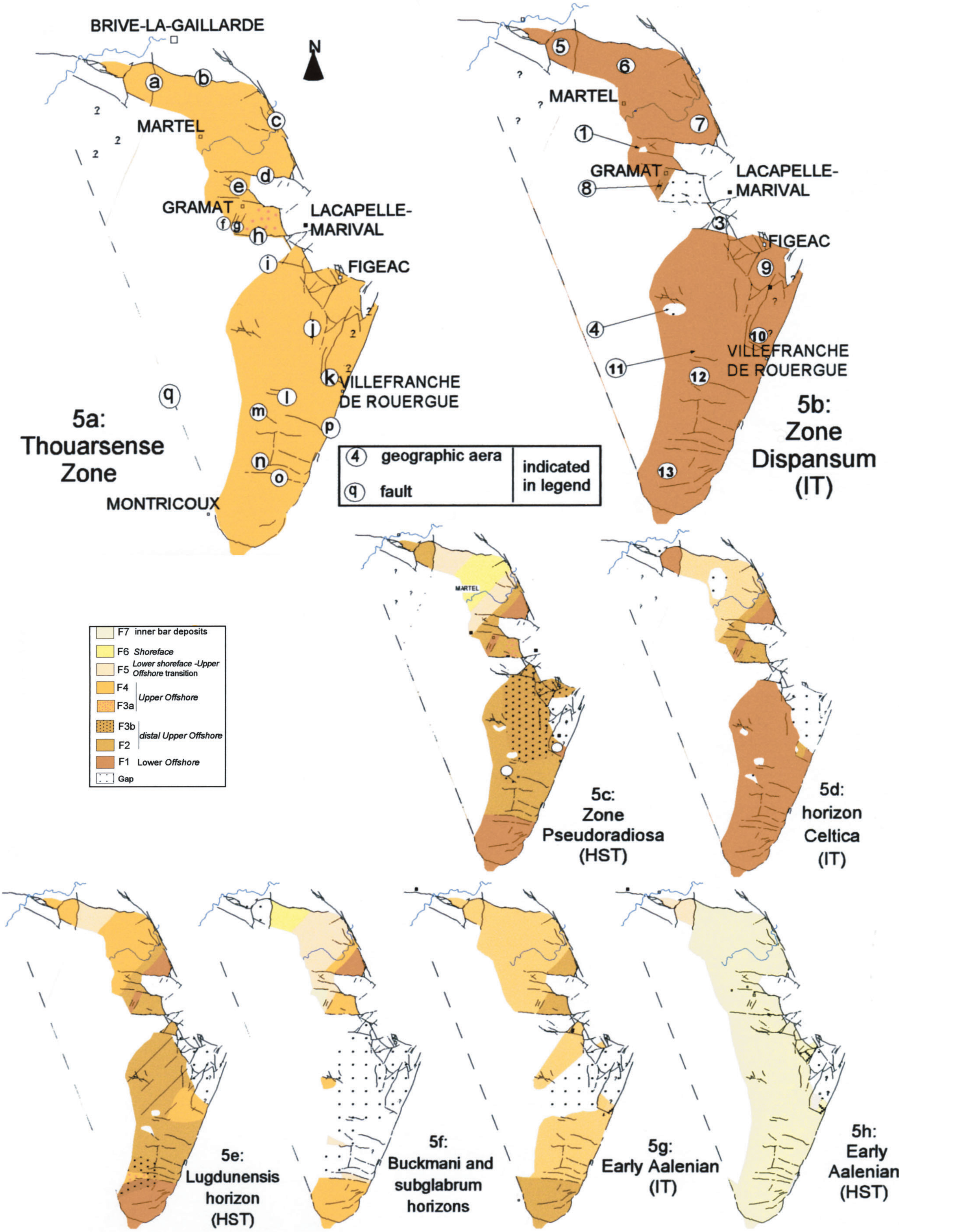

FIG. 5. – Palaeoenvironmental map. Palaeoenvironment distribution and evolution during the Upper Toarcian and Early Aalenian.
1: Gouffre du Réveillon; 2: Thémines; 3: Mas de Gendre; 4: St-Martin-Labouval area; 5: Le Pouch area – La Roche; 6: “haut-fond de La Gironie”; 7: Autoire; 8: Gramat; 9: Figeac-Capdenac area; 10: St Rémy area; 11: Janas (Promilhanes-Martiel area); 12: Cros area; 13: “Grésignol” area; a: Lissac fault; b: Condat-Meyssac fault (F.); c: Cornac-Argentat F.; d: Padirac F.; e: Alvignac F.; f: Cuzoul F.; g: Longayrie F.; h: Bourg F.; i: Livernon F; j: Ambeyrac F.; k: Toulonjac F.; l: Mémer F.; m: St Projet F.; n: Gouvern F.; o: St-Antonin F.; p: Villefranche-de-Rouergue F.; q: West-Quercy Lineament (*linéament ouest-quercynois*).

FIG. 5. – *Cartes paléoenvironnementales. Distribution et évolution des environnements de dépôts au cours du Toarcien supérieur et de l’Aalénien inférieur.*

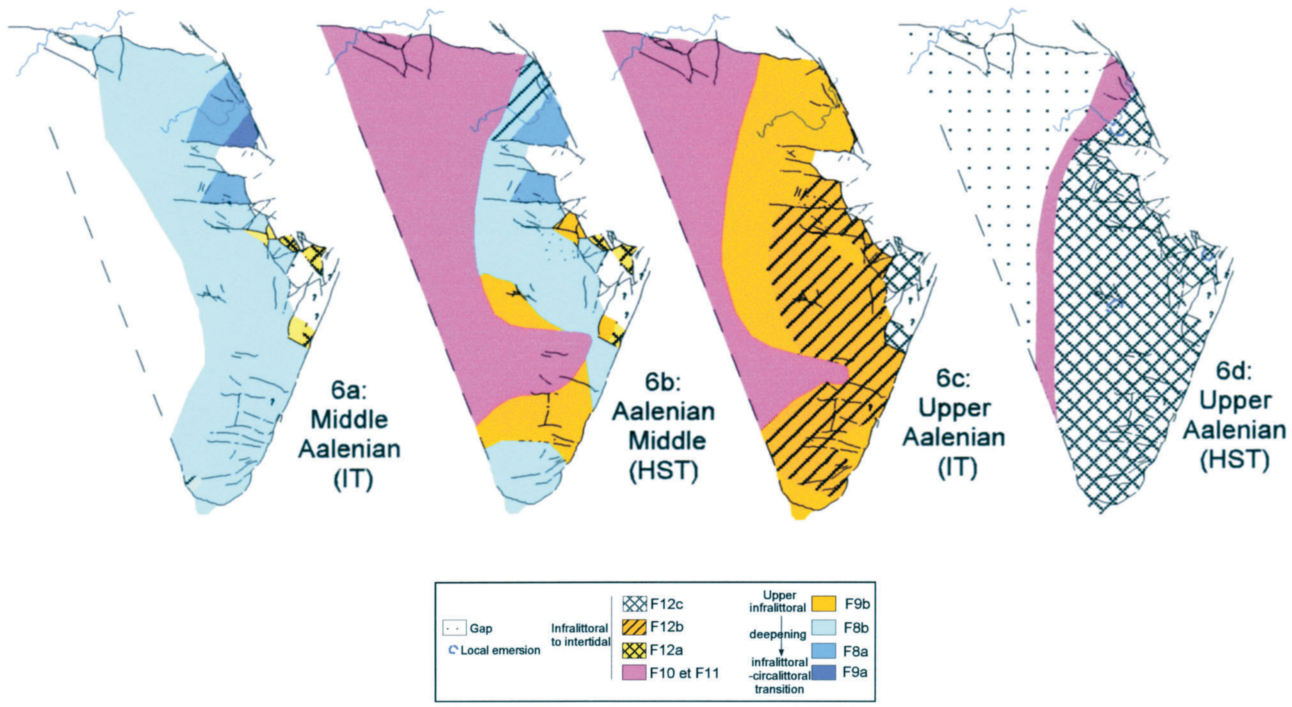

FIG. 6. – Palaeoenvironmental map. Palaeoenvironment distribution and evolution during the Middle and Upper Aalenian.
FIG. 6. – *Cartes paléoenvironnementales. Distribution et évolution des environnements de dépôts au cours de l'Aalénien moyen et supérieur.*

The basis of the Upper Aalenian: new transgressive phase

At the beginning of the Upper Aalenian (fig. 6c), the inner oolitic bar deposits (facies F10 and F11) migrate slightly toward the west while the more or less dolomitized pelletoid facies becomes widespread. In every section, the sedimentation is homogeneous but the increase in bed thickness suggests an increase in the available space balanced by carbonate bio-production. This rise of sea level (transgressive interval of SD5) is also evidenced by aggradation of oolitic bars and by the migration toward the west of the inner oolitic bar deposits.

Summit of the Aalenian: end of the sedimentary filling

Sedimentary filling (HST, SD5) becomes more pronounced and ends with the occurrence of dolomicrites and recrystallized limestones with ghosts of ooids (fig. 6d). In the topmost part, below the unconformity, clues of evaporitic and confined depositional environments are observed. Evaporitic environments are suggested by the occasional occurrence of geoids filled with quartz and calcite (sparite). These are either randomly distributed or concentrated along stratifications. They disappear, with the appearance of the oolitic limestones, above the discontinuity indicating the Aalenian-Bajocian boundary. The diagenetic survey of these geoids showed that siliceous cements contain some fine anhydrite inclusions. They are interpreted as old anhydrite nodules [Maliva, 1987; Durlet *et al.,* 2000]. The sediment deformation around the geoids shows that the anhydrite nodules were formed very early, before compaction, thus demonstrating the existence of a sebkha environment at the end of the Aalenian. Some ghosts of gypsum structures (mainly chicken wire) also appear in a few rare dolomicrites situated under the Aalenian-Bajocian boundary.

Below the uppermost discontinuity, the geoids are associated with dissolution cavities filled by laminated internal sediments. The material refilling the cavities consists of calcareous-clayey, ferruginous, polyphased (red or orange coloured) sediments. Boichard and Drullion [1982] indicate comparable cavities, but without refilling. We interpret these and their refilling as palaeokarst structures, which formed during an emersion phase at the end of the Aalenian or at the beginning of the Bajocian. Emersion is recorded notably in an area that corresponded earlier to a subsidence area (SE of the "Causse de Martel"). In the northwestern part of the "Causse de Martel", these clues have not been recorded because of the absence of deposits.

The Aalenian-Bajocian boundary is generally represented by an erosive surface (SB, SD6). During the Bajocian, the sedimentation is more uniform. Oolitic limestones, deposited in the whole region, indicate a new phase of flooding (IT, SD6).

DISCUSSION: ALLOCYCLIC CONTROLS

The arrangement of deposits and the nature of sedimentation are controlled by various interdependent factors. The data acquired previously and the advanced interpretations allow us to debate the influence of local and/or regional scale factors (short and medium wavelength tectonic factors) and of more global allocyclic factors.

Relative sea level variations: eustatic or tectonic control?

The Toarcian-Aalenian deposits reveal a long-term regressive trend (second order). In the Quercy basin, the regression began during the middle Toarcian and finished at the end of the Aalenian (intra or uppermost part of the Comptum zone). The maximum of regression is evidenced either by an erosional surface or by the development of evaporites and locally by emersion (palaeokarst). The following transgressive episode is expressed by the appearance of oolitic limestones over the whole basin.

Such an evolution is well known in most basins that have Tethyan or Atlantic affinities. It appears by the development of carbonate platforms or by the presence of important sedimentary hiatuses. The maximum of transgression, dated from the Bifrons Zone and Subzone, is often synchronous on a European scale. The maximum of regression is, however, diachronous. It is dated:

– as Upper Toarcian in the Betic cordillera [O'Dogherty *et al.*, 2000];

– as Lower Aalenian in the Basque-Cantabrian basins and in the Asturies [Aurell *et al.*, 2003];

– from the top of the Murchisonae zone in the Paris Basin, the Grands-Causses and Basse-Provence basins [Floquet *et al.*, 2000];

– as Middle Aalenian in the Iberian basin [Aurell *et al.*, 2003] and in the western margin of the subalpine basin [Razin *et al.,* 1996];

– and from the top of the Concavum zone in the Quercy Basin (this study).

Such a diachronous record suggests a tectono-eustatic origin and coincides with the mid-Cimmerian event recorded in NW European basins.

At the third order scale, the Toarcian-Aalenian Quercy set is arranged in 5 depositional sequences *sensu* Haq *et al.* [1987] and Vail *et al.* [1991] while Hardenbol *et al.* [1998] indicate 4 depositional sequences for the same interval of time. The major difference therefore consists in the identification of an additional sequence in the uppermost Toarcian (fig. 4). Thus, in the present state of knowledge and lack of arguments attesting perfect synchronism of the sequence boundaries at the scale of European basins, it is not possible to provide evidence whether the variations of the relative sea level at the third order scale result from regional tectonic factors and/or eustatic variations.

Synsedimentary tectonics

Indications of synsedimentary tectonics in the Quercy

The influence of local tectonics, including active faults during the interval studied, is suggested by:

– variations of thickness and migration of sedimentary accumulation zones in the Gramat area: for example, in the Dispansum and Pseudoradiosa zones and the Mactra horizon (fig. 4), the sedimentary accumulation zone is located in the "Gouffre du Réveillon" area; in the Lower Aalenian, it is situated in the Moulin de Tournefeuille area (fig. 4);

– increasing subsidence along the Hercynian structures. In the Upper Toarcian, the most depressed zones are near the Villefranche and the Cornac-Argentat Hercynian faults;

– facies variations, notably on both sides of the Alvignac fault. In the Dispansum, Pseudoradiosa zones and the Mactra horizon, shoreface sedimentation occurred in "Gouffre du Réveillon" area, while upper offshore sedimentation characterises Moulin de Tournefeuille area (fig. 5b and 5c). In the uppermost Toarcian a reverse trend is observed (fig. 5f);

– structuring in small blocks implying the appearance of shoals. During the Upper Toarcian (Dispansum zone), partition of the Quercy platform can be observed and therefore the individualisation of a mosaic of rhombohedric blocks of variable size (decakilometrical scale: Martel area; kilometrical scale: St. Rémy area). Some of these existed as early as the middle Lias (Figeac-Capdenac shoal, Cubaynes [1986]).

These features reveal a meaningful and continuous tectonic activity from the Upper Toarcian (Dispansum, Pseudoradiosa and Aalensis zones) to the Middle Aalenian. It is expressed by activity of faults oriented East-West, N-S to N020 and N160-N170. During these times, there are changes in minor fault activity (fig. 7). In the Upper Toarcian NE-SW, NW-SE and E-W faults are preferentially involved. In the Lower and Middle Aalenian, the peripheral Hercynian faults (Villefranche-de-Rouergue fault, Cornac-Argentat faults and west-Quercy lineament) show increased activity. The E-W structures are still active, but a decreasing activity of the NE-SW minor faults is recorded.

The presence of a depressed zone at the southwestern extremity of the Villefranche-de-Rouergue fault and a shoal (Figeac-Capdenac shoal) at its northwestern extremity (e.g. during the Lugdunensis horizon, see fig. 5e), suggest a dextral sense of slip for this fault [Chinnery, 1961]. The same reasoning leads us to propose that motion, also towards the right of the Cornac-Argentat faults (to the East of Autoire) and of Meyssac (to the North), accounts for the individualisation of the "Gironie" shoal. Strike-slip motions along some major Hercynian faults notably allow the appearance and/or the reactivation of transverse faults.

Comparisons with other sedimentary basins

In other French regions, such as the Paris Basin, Burgundy, Jura Mountains and the Subalpine Basin, local tectonic events occurring at the same age are indicated by facies variations, synsedimentary fractures and veins, and migration of subsidence zones [Razin *et al.*, 1996; Durlet *et al.*, 1997; Rousselle, 1997; Durlet and Thierry, 1999; Gély and Lorenz, 2000; Robin *et al.*, 2003; de Graciansky and Jacquin, 2003]. During the Lias-Dogger, the Ardèche area [Razin *et al.*, 1996] was structured by a mosaic of faulted blocks bordered by primary NNE-SSW (Cévenole direction) and secondary NW-SE faults. At the Lias-Dogger transition, this region shows variations in the thickness of sedimentary deposits [Elmi, 1990], unequal rates of subsidence on the various tilted blocks, local uplift and a significant synsedimentary block faulting activity [Razin *et al.*, 1996]. In the Paris Basin, the Middle Toarcian – Lower Aalenian interval (first part of the Toarcian – Bajocian regressive cycle) was a period of flexuration [de Graciansky and Jacquin, 2003]. The Early Aalenian unconformity records an accentuation of the flexuration initiated during the Lias, with erosion on the eastern and western borders of the Paris Basin [Robin, 1997]. Increased tectonic activity and/or of

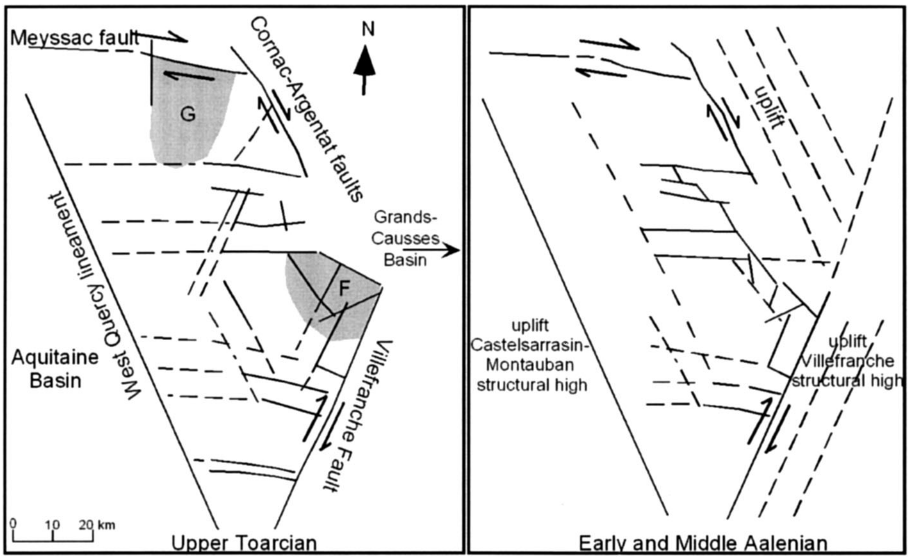

FIG. 7. – Locations of the main active faults and regional tectonic context during Upper Toarcian and Lower-middle Aalenian.
FIG. 7. – *Localisation des principales failles actives et interprétation du contexte tectonique régional au Toarcien supérieur et à l'Aalénien inférieur à moyen. Mouvements décrochants dextres des grands accidents régionaux.*

change in the stress orientation is also recorded in other basins, notably in Morocco [Laville and Piqué, 1991; El Hammichi *et al.*, 2002], in Algeria [Mekahli and Elmi, 2000], in Atlasic Tunisia [Soussi, 2003] and in central Arabia [Vaslet *et al.*, 2000]. A phase of uplift occurred in the North Sea [Ziegler, 1988; Underhill *et al.,* 1993; Jacquin *et al.*, 2000], which extended to the Paris Basin.

Sedimentary regime change at the Lias – Dogger transition: tectonic, climatic or eustatic origin?

The major palaeoenvironmental event recorded in the Quercy Basin corresponds to the passage from an open platform (Toarcian-Lower Aalenian) to a protected platform (Middle and Upper Aalenian). This change, which coincides with the maximum of tectonic activity and a significant reactivation of the Hercynian structures, seems therefore to be tectonic in origin. The positive vertical movements of the basin margins appear to have partially isolated the Quercy Basin. The uplift of the Villefranche shoal would have isolated the Quercy toward the east and a N-S oriented oolitic bar [Carozzi *et al.*, 1972] appeared to the west on the Castelsarrasin-Montauban shoal. Connections between the Quercy platform, the western part of the Aquitaine Basin and the "Grands-Causses" Basin (to the east) [Carozzi *et al.*, 1972; Ciszak *et al.*, 2000] were thus reduced (fig. 8). During the Bajocian, the Quercy, the "Grands-Causses" and the Cévenole border became integrated in the "Occitan" shoal [Delfaud, 1973]. Mud flat sedimentation, isolated from the open seas by a N-S oriented oolitic bar, on the Occitan shoal developed. The information deduced from our study shows that the Occitan shoal did not individualise abruptly in the Bajocian but progressively during the Dogger. The Quercy first became isolated from the Atlantic sea (lower to Middle Aalenian) and then, in a second step, the "Grands-Causses" Basin was isolated from the Tethys (Bajocian).

Alternatively, a climatic hypothesis can be proposed to explain the facies change in the Middle Aalenian. Many works point out a climatic evolution between the middle Toarcian and the Aalenian-Bajocian transition, notably in the western European zone. Ruffell *et al.* [2002], referring to various studies, show that a rather humid (tropical) climate progressively gave way to a more arid one. The minimum of humidity was reached in the Early Bajocian, presumably accompanied by a maximum of surface water temperature (near 30° C) as suggested by Lecuyer *et al.* [2003] for many French basins.

In the Quercy basin, clay mineralogical analyses coupled with the study of palynological associations [Lézin, 2000], highlight possible climatic control. The clay fractions of 112 samples from three outcrops (fig. 1), Bruniquel (southern Quercy), Thémines (central Quercy) and Autoire (northern Quercy), were analysed by X-ray diffraction (XRD). Because of strong analogies in the variations of clay mineral assemblages at the 3 sites, only the results obtained for the Autoire section are presented here (fig. 9). The clay assemblages are dominated by illite, random illite/smectite mixed-layers and kaolinite, with small proportions of chlorite. Their mainly (or even exclusively) detrital origin has already been demonstrated [Lézin, 2000]. Only scarce data are available on Aalenian clay assemblages. In the Paris Basin [Debrabant *et al.*, 1992] and on the northern border of the Central Massif [Delavenna *et al.*, 1989], the assemblages are also dominated by illite and kaolinite. These assemblages seem representative of hot and humid

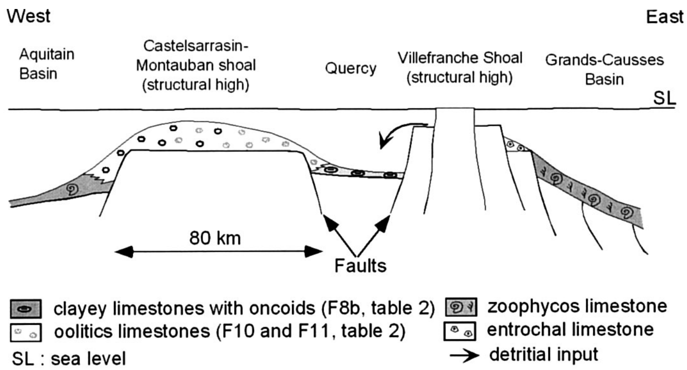

FIG. 8. – East-West schematic section showing the isolation of the Quercy platform during middle Aalenian.
FIG. 8. – *Coupe schématique d'orientation Est-Ouest montrant l'isolement de la plate-forme quercynoise à l'Aalénien moyen.*

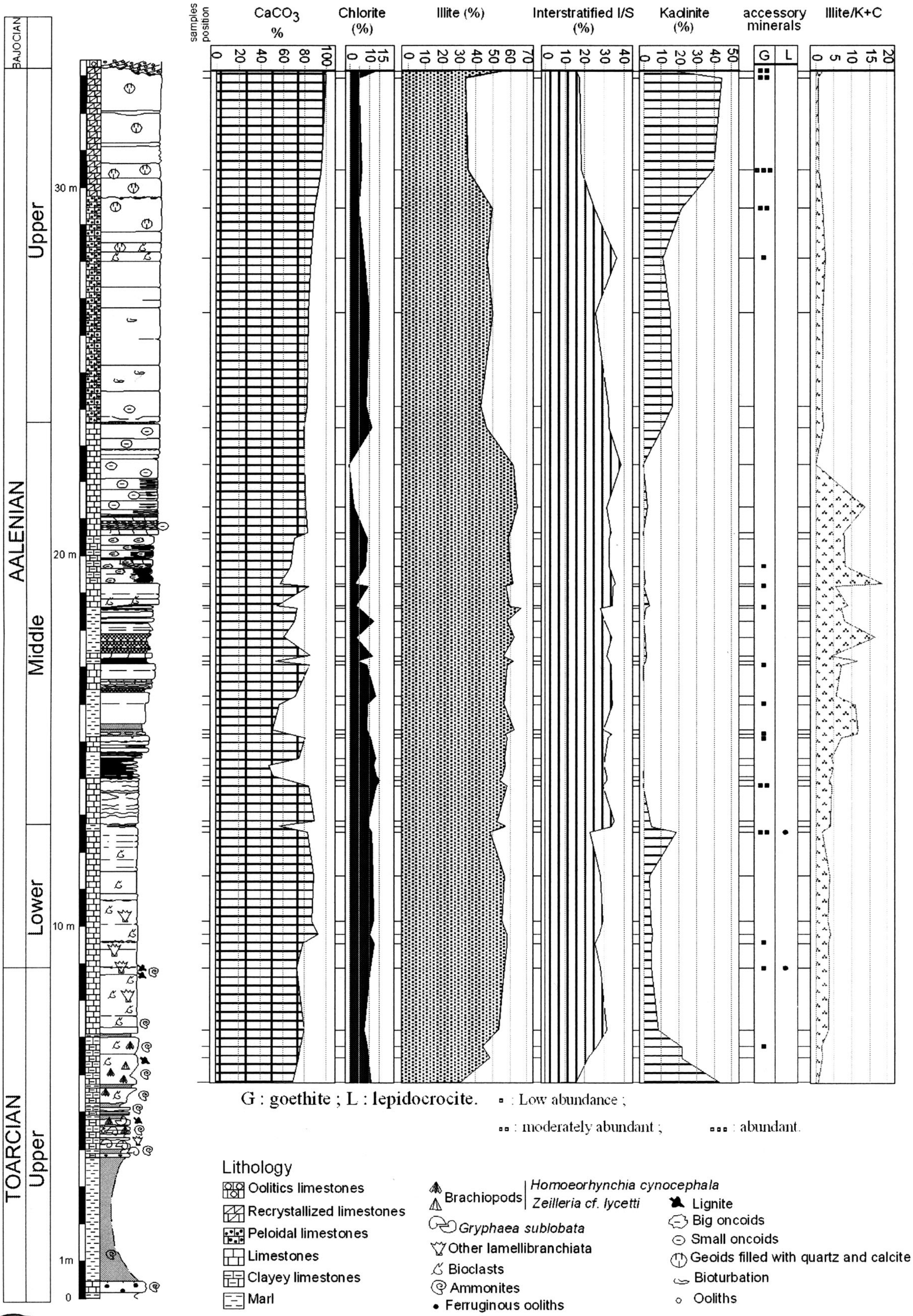

FIG. 9. – Variations in the mineralogical composition of Upper Toarcian – Aalenian deposits (Autoire section).
FIG. 9. – *Variations de la composition minéralogique des dépôts du Toarcien supérieur – Aalénien de la coupe d'Autoire.*

climates (tropical climate) of the Lias-Dogger transition, also highlighted in various regions by Wang *et al.* [1997] on the basis of palynological data and in Yorkshire by Hesselbo *et al.* [2003].

In the Quercy area, the proportions of kaolinite show significant fluctuations with time.

In the Upper Toarcian/Lower Aalenian interval, the proportions of kaolinite decrease progressively from 40% to 5%. Upward, in the Middle Aalenian, only traces of kaolinite occur occasionally. In the Upper Aalenian, the proportions of this mineral increase again while those of illite and random illite/smectite mixed-layers decrease.

The decreasing proportions of kaolinite in the Upper Toarcian are accompanied by an abundance of *Classopolis* sp. and *Deltoidospora* sp. [Lezin, 2000]. This association and the evolution of the percentages of kaolinite suggest a hot and more and more dry tropical to subtropical climate [Wang *et al.*, 2005] that seems to have lasted during the Lower Aalenian. In the Middle Aalenian, the scarcity of kaolinite suggests a drier climate and arid conditions. However, the diachronism of the decreasing proportions of kaolinite at the basin scale (earlier in the South [early Aalenian] than in the North [Middle Aalenian; Lézin, 2000]), indicate that climate is probably not the main environmental factor responsible for the composition of the clay assemblages. The absence of kaolinite during the Middle Aalenian is not recorded on the northern border of the Central Massif [Delavenna *et al.*, 1989] nor in Poland [Simkevicius *et al.*, 2003], which suggests that it is also related to local conditions.

Increasing proportions of kaolinite characterising Late Aalenian deposits would suggest a more humid climate. But this trend is accompanied by the progressive appearance of evaporites, and palynological associations indicate more arid conditions than in the Upper Toarcian. The increasing proportions of kaolinite took place during the development of more proximal facies in the protected platform context, suggesting that differential settling processes of clay minerals have played a significant role, kaolinite being preferentially deposited in inner environments, than illite and illite-smectite mixed-layers [Chamley, 1989].

The diachronism of kaolinite disappearance balanced by increasing proportions of illite, may indicate an uplift and a diachronic erosion of the various blocks that compose the shoal with, first, an uplift of the southeastern blocks (Villefranche shoal) during the Lower Aalenian, then an uplift of the northwestern blocks (SW of the Central Massif) during the Middle Aalenian. The reappearance of this clay mineral at the top of Middle Aalenian, associated with an increase in carbonate production, apparently records the end of the uplift. This interruption of connections with the Tethys Ocean, linked with the uplift of the oriental blocks, is confirmed by palynology. The Toarcian dinoflagellate cyst assemblages exhibited characteristics of both the Boreal and Tethyan realms, whereas the Aalenian marine palynofloras were of Boreal affinity [Bucefalo Palliani and Riding, 1997]. The uplift of the southeastern and northwestern blocks, leading to their emersion [Courjault-Rade *et al.*, 2000], could have generated the disappearance of the plant cover, and therefore weakened the development of kaolinite and accentuated the contribution of illite coming from the direct erosion of the continental bedrock. The disappearance of spores and pollens may be then linked to the disappearance of the plant cover. At the same time, the uplift of the Castelsarrasin-Montauban block, to the west, may have permitted the development of an oolithic bar that reduced the communications with the Atlantic domain. During the late Aalenian, the end of the uplift of the shoal peripheral to the basin may explain the resumption of chemical weathering on emerged zones and therefore the reappearance of the kaolinite in very small quantities (but in high proportions of the clay fraction because of differential settling) in the carbonate deposits. The absence of spores and pollens may indicate the difficulty of new plant colonisation, probably in relation with the more arid character of the climate. The evaporitic episode at the Aalenian-Bajocian boundary may then result from both the confinement of the sedimentary area and an increase in the temperature with probably more arid conditions than in the Upper Toarcian.

The comparison of the field, palynological and mineralogical data therefore suggests a predominance of tectonic control of the sedimentary regime change in the Middle Aalenian, leading to the isolation of the platform. The "minor" climatic variations only added to this isolation because they enhance carbonate production.

Structural model

From the post-Paleozoic to the Middle Jurassic, the Gondwana break-up was governed by the southward propagation of the Arctic – North Atlantic rift (Norwegian, Greenland rift system) and the westward propagation of the Tethys Ocean [Ziegler, 1988]. The evolution of Triassic and Jurassic rifts in the North and Central Atlantic area can be related to the propagation of these two rifts [Ziegler, 1988].

This geodynamic context led to major paleogeographic changes, at the Lias-Dogger transition (Upper Toarcian to Early Bajocian): (i) a well expressed rifting to drifting phase with several synsedimentary faults and tilting blocks on the Ligurian margin [Lemoine and Graciansky, 1988; Ziegler, 1988; Graciansky *et al.*, 1993]; (ii) an uplift phase affecting the North Sea rift [Ziegler, 1982]; (iii) and the first crustal separation on the future Central Atlantic area [Piqué et Laville, 1995].

This acceleration of the Pangea break-up during the Lias-Dogger transition led to lesser kinematics distortion in most Peri-Tethyan platforms than on Tethys or Proto-Atlantic margins. Nevertheless, certain researchers have tried to define the stress orientation on these platforms. For example in the Burgundy, Champagne and Jura platforms, a NW-SE extension is documented by synsedimentary normal faults and strike-slip faults [Durlet *et al.*, 1997; Rousselle, 1997; Durlet and Thierry, 1999; Quesne *et al.*, 2000; Wetzel *et al.*, 2003]. In southern Ardèche and in the Cévennes, an extensive component is well expressed by highly subsiding areas bordered by synsedimentary normal faults [Petit *et al.,* 1973; Elmi, 1984; Razin *et al.*, 1996].

Meanwhile, a compressive tectonic component has also been evoked on other platforms. In the Paris Basin, for example, Robin *et al.* [2003] suggest a short wavelength E-W to ENE-WSW compression during Aalenian and Bajocian times. Southward, in Spain and in Morocco, several subsiding transtensional rift basins developed along paleotransfer faults. These transfer faults permitted the drift of Africa toward the east and consecutively the Central

Atlantic opening [Ibouh *et al.*, 1994; Mouguina *et al.*, 2000; El Kochri and Chorowicz, 1996, Piqué et Laville, 1995].

The dextral strike-slip movements (fig. 7) and the sedimentary regime change in the Middle Aalenian recorded in the Quercy, just as the palaeotopographic modifications recorded in adjacent areas, suggest that the Toarcian-Aalenian regressive cycle was controlled by the resultant of two intimately related types of deformation:

1) lithospheric scale (long-wavelength) deformation, which could be of thermal and/or isostatic origin, causing variations in regional subsidence that could have negative values during periods of rifting;

2) more local (short or medium wavelength) extensional tectonic deformation developing during periods of uplift or slow regional subsidence, and which was expressed by synsedimentary block faulting activity.

CONCLUSION

The sedimentological evolution of the Quercy Basin, based on a multi-disciplinary approach, allows us to refine the chronology of the main events previously known in most western European basins during the Upper Toarcian – Bajocian interval.

1) The geometry of sedimentary deposits was under continuous tectonic control from the Upper Toarcian (Pseudoradiosa zone) to the Bajocian. The maximum tectonic activity is expressed by the uplift of the peripheral blocks with the basin and induced its semi-isolation. This event is dated at the top of the Opalinum zone and at the base of the Murchisonae zone. It could be connected to the "mid-Cimmerian" event. It resulted from the additional effects of Tethys rifting, Central Atlantic opening and North Sea rifting. In the Quercy Basin, the continuous record of sedimentation indicates that this event had moderate consequences on the palaeogeographic evolution.

2) The maximum of tectonic activity and the maximum of regression at the 2nd order scale were diachronous. In the Quercy Basin, the maximum of regression is dated at the Concavum zone or the base of the Bajocian.

3) The Toarcian-Aalenian Quercy set is arranged in 5 depositional sequences (3rd order) *sensu* Haq *et al.* [1987] and Vail *et al.* [1991]. At this third order scale, it was not possible to decipher between the influence of relative sea level variations resulting from regional tectonic factors and eustatic variations.

4) From a climatic "point of view", the passage from a tropical climate to a more arid climate seems to have had little impact on the bio-sedimentary evolution.

Acknowledgements. – The authors thank reviewers O. Dugué and S. Elmi for their helpful comments and suggestions which helped improve an earlier version of the manuscript. We wish to express sincere thanks to Y. Alméras and G. Lachkar for respectivly brachiopod determination and palynological analysis.

References

ALMÉRAS Y. & MOULAN G. (1982). – Les Térébratulidés liasiques de Provence (paléontologie – biostratigraphie – paléoécologie – phylogénie). – *Docum. Lab. Géol. Lyon*, 365 p.

AURELL M., ROBLES S., BADENAS B., ROSALES I., QUESADA S., MELENDEZ G. & GARCIA-RAMOS J. C. (2003). – Transgressive-regressive cycles and Jurassic palaeogeography of northeast Iberia. – *Sediment. Geol.*, **162**, 239-271.

BOICHARD R. & DRULLION G. (1982). – Genèse et évolution diagénétique des formations carbonatées granulaires du Bajocien du Quercy: Evolution de leurs propriétés réservoirs. – Doctoral thesis, Université de Bordeaux III, 345 p.

BRANGER P. (1989). – La marge Nord-Aquitaine et le seuil du Poitou au Bajocien: stratigraphie séquentielle, évolution biosédimentaire et paléogéographie. – Doctoral thesis, univ. Poitiers, 1-2, 206 p.

BUCEFALO PALLIANI R. & RIDING J.B. (1997). – The influence of paleoenvironmental change on dinoflagellate cyst distribution. An example from the Lower and Middle Jurassic of Quercy, southwest France. – *Bull. Centre rech. Expl. Elf-Aquitaine*, Pau, **21**, 1, 107-124.

CAROZZI A.V., BOUROULLEC J., DELOFFRE R. & RUMEAU J.L. (1972). – Microfaciès du Jurassique d'Aquitaine. – *Bull. Cent. Rech. Pau*, SNEAP, vol. sp. n°1, 200 pl., 14 tabl., 594 p.

CHAMLEY H., (1989). – Clay sedimentology. – Springer, 623 p.

CHINNERY M.A. (1961). – The deformation of the ground around surface faults. – *Bull. Seismol. Soc. Amer.*, **51**, n°3, 355-372.

CISZAK R., PEYBERNÈS B., FAURÉ PH. & THIERRY J. (2000). – Géométrie et enchaînement des séquences de dépôt aaléno-bajociennes dans les Grands-Causses (France). – *Strata*, (1), **10**, 1 fig., 61-63.

CONTINI D., ELMI S., MOUTERDE R. & RIOULT M. (1997). – Biozonation de l'Aalénien. *In*: biostratigraphie du Jurassique Ouest-Européen et méditerranéen: zonations parallèles et distribution des invertébrés et microfossiles. – *Bull. Centre Rech. Elf Explor. Prod.*, **17**, 6 fig., 79 tab., 42 pl., 440 p.

COURJAULT-RADÉ P., BOYCE A., FALLICK A., MUNOZ M. & TOLLON F. (2000). – La transition Lias-Dogger: un épisode hydrothermal à la bordure orientale du bassin d'Aquitaine (Albigeois et NW Montagne Noire). – *Strata*, (1), **10**, 1 fig., 64-66.

CROS P.G. (1979). – Genèse d'oolithes et de grapestones, plate-forme des Bahamas (Joulters Cays, Grand Banc). – *Bull. Centre Rech. Explor. Elf Aquitaine*, **3**, 1, 9 fig., 15 pl., 63-139.

CUBAYNES R. (1986). – Le Lias du Quercy méridional. Etude lithologique, biostratigraphie, paléoécologie et sédimentologie. – *Strata*, (2), **6**, 574 p.

CUBAYNES R. & FAURÉ PH. (1981). – Première analyse biostratigraphique du Lias supérieur du Sud-Quercy (bordure Nord-Est Aquitaine). – *C. R. Acad. Sci.*, Paris, (2), **292**, 1031-1034.

DEBRABANT P., CHAMLEY H., DECONINCK J.F., RECOURT P. & TROUILLER A. (1992). – Clay sedimentology, mineralogy and chemistry of Mesozoic sediments drilled in the northern Paris Basin. – *Scientific Drilling*, vol.3, 138-152.

DELAVENNA M.F., STEINBERG M., TRAUTH N. & HOLZAPFFEL T. (1989). – Influence des cycles eustatiques et de la tectonique synsédimentaire sur la minéralogie du Lias et du Dogger du forage de Sancerre-Couy (Cher). Programme Géologie Profonde de la France. – *C. R. Acad. Sci.*, Paris, II, **308**, 111-116.

DELFAUD J. (1973). – Un élément majeur de la paléogéographie du sud de la France au Jurassique moyen et supérieur: le Haut-fond Occitan. – *C. R. somm. Soc. géol. Fr.*, 58-59.

DURLET C., JACQUIN TH. & FLOQUET M. (1997). – Tectonique synsédimentaire distensive dans les calcaires aaléno-bajociens du seuil de Bourgogne (France). – *C. R. Acad. Sci.*, Paris, **324**, 12, 1001-1008.

DURLET C., LÉZIN C., PÉLISSIÉ TH., LORENZ J. & GELY J.-P. (2000). – Les indices d'émersion dans les dépôts aaléno-bajociens des pourtours du Massif central. – *Strata*, (1), **10**, 56-58.

DURLET C. & THIERRY J. (1999). – Modalités séquentielles de la transgression aaléno-bajocienne sur le sud-est du Bassin parisien. – *Bull. Soc. géol. Fr.,* **171**, 3, 327-339.

EL HAMMICHI F., ELMI S., FAURE-MURET A. & BENSHILIL K. (2002). – Une plate-forme en distension, témoin de phases pré-accrétion téthysienne en Afrique du Nord pendant le Toarcien-Aalénien (synclinal Iguer Awragh-Afennourir, Moyen Atlas occidental, Maroc). – *C. R. Geoscience,* **334**, 1003-1010.

EL KOCHRI A. & CHOROWICZ J. (1996). – Oblique extension in the Jurassic trough of the central and eastern High Atlas (Morocco). – *Can. J. Earth Sci.*, **33**, 84-92.

ELMI S. (1984). – Tectonique et sédimentation jurassique. *In*: S. DEBRAND-PASSARD, Ed., Synthèse géologique du Sud-Est de la France. – *Mém. BRGM*, 166-175.

ELMI S. (1990). – Stages in evolution of Late Triassic and Jurassic platforms: the examples from the western margin of the Subalpine Basin (Ardèche, France). – *SEPM. Spec. Publ., Intern. Assoc. Sedim.*, **9**, 109-144.

ELMI S., RULLEAU L., GABILLY J. & MOUTERDE R. (1997). – Biozonation du Toarcien. *In:* Biostratigraphie du Jurassique Ouest-Européen et méditerranéen: zonations parallèles et distribution des invertébrés et microfossiles. – *Bull. Centre Rech. Elf Explor.-Prod.*, **17**, 6 fig., 79 tab., 42 pl., 440 p.

FAURÉ PH., LÉZIN C. & CUBAYNES R. (2000). – Le découpage biochronologique du Toarcien supérieur par les ammonites (zones à Pseudoradiosa et à Aalensis) du Sud de la France (Lot, Lozère, Aveyron). – *Strata*, (1), **10**, 127-129.

FLOQUET M., MARCHAND D., SIDA B. & CONTINI D. (2000). – Monticules micritiques à spongiaires et discontinuités sédimentaires marqueurs de l'ennoiement de la plate-forme carbonatée de basse Provence à l'Aalénien supérieur-Bajocien inférieur. – *Strata*, (1), **10**, 83-85.

GELY J.P & LORENZ J. (2000). – Le passage Lias-Dogger dans le Berry entre les blocs armoricain et bourguignon. – *Strata*, (1), **10**, 53.

GUILLOCHEAU F., ROBIN C., ALLEMAND P. BOURQUIN S., BRAULT N., DROMART G., FRIEDENBERG R., GARCIA J.-P., GAULIER J.-M. & GAUMET F. (2000). – Meso-Cenozoic geodynamic evolution of the Paris Basin: 3D stratigraphic constraints. – *Geodin. Acta*, **13**, 189-246.

GRACIANSKY P.C. de, DARDEAU G., DUMONT T., JACQUIN TH., MARCHAND D., MOUTERDE R. & VAIL P. R. (1993). – Séquences de dépôt, cycles transgressifs-régressifs et tectonique d'extension: l'exemple du bassin dauphinois dans la région de Digne au Lias et au Dogger. – *Bull. Soc. géol. Fr.*, **XVI**, 709-718.

GRACIANSKY P.C. de & JACQUIN TH. (2003). – Evolution des structures et de la paléogéographie au passage Lias-Dogger dans le bassin de Paris d'après les données de subsurface. – *Bull. Soc. géol. Fr.,* **174**, 1, 3-17.

HAQ B.U, HARDENBOL J. & VAIL P.R. (1987). – Chronology of fluctuating sea levels since the Triassic. – *Science*, **235**, 1566-1567.

HARDENBOL J., THIERRY J., FARLEY M.B., JACQUIN TH., GRACIANSKY P.C. de & VAIL P.R. (1998). – Mesozoic and Cenozoic sequence chronostratigraphy framework of European basins. *In*: P. C. DE GRACIANSKY, TH. JACQUIN, M.B. FARLEY & P.R. VAIL, Eds., Mesozoic and Cenozoic sequence stratigraphy of European Basins. – *SEPM Sp. Publ.*, **60**, chart 6.

HESSELBO S.P., MORGANS-BELL H.S., MCELWAIN J.C., REES P.M., ROBINSON S.A. & ROSS C.E. (2003). – Carbon-cycle perturbation in the Middle Jurassic and accompanying changes in the terrestrial paleoenvironment. – *J. Geol.,* **111**, 3, 259-276.

IBOUH H., BOUABDELLI M. & ZARGOUNI F. (1994). – Indices de tectonique synsédimentaire dans les dépôts aaléno-bajociens de la région d'Ilmilchil (Haut Atlas Central, Maroc). – Proc. 3rd Internat. Meeting in Aalenian and Bajocian Stratigraphy. – *Miscellaneo del Servizio Geologico Nazionale*, **5**, 305-310.

JACQUIN T., DARDEAU G., DURLET C., GRACIANSKY P.C. de & HANTZPERGUE P. (1998). – The North sea cycle– An overview of transgressive-regressive facies cycles in western Europe. *In*: P. C. de GRACIANSKY, TH. JACQUIN, M.B. FARLEY & P.R. VAIL, Eds., Mesozoic and Cenozoic sequence stratigraphy of European basins. – *SEPM sp. publ.*, **60**, 445-466.

JACQUIN T., DUNAY R.E. & THOMSEN M. (2000). – The Brent delta complex: a record of the Mid-Cimmerian unconformity in the north Viking graben (North Sea)? – *Strata*, (1), **10**, 1 fig., 1 tabl., 39-42.

LAVILLE E. & PIQUÉ A. (1991). – La distension crustale atlantique et atlasique au Maroc au début du Mésozoïque: le rejeu de structures hercyniennes. – *Bull. Soc. géol. Fr.,* **162**, 1161-1171.

LEMOINE M. & GRACIANSKY P. C. de (1988). – Histoire d'une marge continentale passive: les Alpes occidentales au Mésozoïque. – *Bull. Soc. géol. Fr.*, (8), **IV**, 597-600.

LÉZIN C. (2000). – Analyses des faciès et stratigraphie intégrée: application aux événements du passage Lias-Dogger sur la plate-forme du Quercy. – Doctoral thesis, Univ. Paul Sabatier, Toulouse III, 317 p.

LÉZIN C., BONNET L., REY J., CUBAYNES R. & PÉLISSIÉ TH. (2000). – Contribution de l'analyse quantitative des faciès aux corrélations stratigraphiques, exemple du Toarcien supérieur-Aalénien dans le Quercy (SW France). – *Bull. Soc. géol. Fr.,* **171**, 1, 91-102.

LEZIN C., CUBAYNES R., FAURE PH., PÉLISSIÉ TH. & REY J. (1997). – Le Toarcien supérieur-Aalénien dans la région de Villefranche-de-Rouergue (Sud-Ouest de la France). Biostratigraphie et évolution sédimentaire. – *Géol. France*, **4**, 3-14.

LECUYER C., PICARD S., GARCIA J.P., SHEPPARD S.M.F., GRANDJEAN P. & DROMART-G. (2003). – Thermal evolution of Tethyan surface waters during the Middle-Late Jurassic; evidence from ?^{18}O values of marine fish teeth. – *Paleoceanography*, **18**, 3, 1-21.

MALIVA R. G. (1987). – Quartz geodes: early diagenetic silicified anhydrite nodules related to dolomitization. – *J. Sediment. Petrol.*, **57**, 6, 1054-1059.

MEKAHLI L. & ELMI S. (2000). – Passage Lias-Dogger dans les monts des Ksour: enregistrement des événements sédimentaires, tectoniques et eustatiques (Atlas saharien, Algérie). – *Strata*, (1), **10**, 92.

MOUGUINA E.M., IBOUH H., CHAFIKI D., BOUABDELLI M. & CANEROT J. (2000). – Tectonique syn-sédimentaire au passage Lias-Dogger associé aux montées précoces des intrusions magmatiques jurassiques dans le Haut Atlas Central (Maroc). – *Strata*, (1), **10**, 106-107.

O'DOGHERTY L., SANDOVAL J., & VERA J. A. (2000). – Ammonite faunal turnover tracing sea level during the Jurassic (Betic Cordillera, southern Spain). – *J. Geol. Soc. London*, **157**, 281-319.

PETIT J.-P., BOUSQUET J.-C. & MATTEI J. (1973). – Glissement synsédimentaire et troncature basale de blocs hettangiens du bord sud du Causse du Larzac entre Arboras et Salces (Languedoc). – *C. R. Acad. Sci.,* Paris, (D227), 1113-1116.

PIQUE A. & LAVILLE E. (1995). – L'ouverture initiale de l'Atlantique central. – *Bull. Soc. géol. Fr.,* **166**, 6, 725-738.

PURSER B.H. (1980). – Sédimentation et diagenèse des carbonates néritiques récents. – Technip éd., Paris, **1**, 366 p.

PURSER B.H. (1983). – Sédimentation et diagenèse des carbonates néritiques récents. – Technip éd., Paris, **2**, 389 p.

QUESNE D., GUIRAUD M., GARCIA J.-P., THIERRY J., LATHUILIÈRE B. & AUDEBERT N. (2000). – Marqueurs d'une structuration extensive jurassique en arrière de la marge nord-téthysienne (monts du Mâconnais, Bourgogne, France). – *C. R. Acad. Sci.,* Paris, **330**, 623-629.

RAT P. (1966). – *Nubecularia reicheli* nov. sp., foraminifère constructeur de fausses oolithes dans le Bajocien de Bourgogne. – *Eclogae Geol. Helv.*, **59/1**, 73-87.

RAZIN P., BONIJOLY D., LE STRAT P., COUREL L., POLI E., DROMART G. & ELMI S. (1996). – Stratigraphic record of the structural evolution of the western extensional margin of the Subalpine Basin during the Triassic and Jurassic, Ardèche, France. – *Mar. Petrol. Geol.*, **13**, 6, 625-652.

RIOULT M, DUGUÉ O., JAN DU CHÉNE R., PONSOT C., FILY G., MORON J.-M & VAIL P.R. (1991). – Outcrop sequence stratigraphy of the anglo-Paris basin, middle to upper Jurassic (Normandy, Maine, Dorset). – *Bull. Centre Rech. Explor. Elf Aquitaine*, **15**, 101-194.

ROBIN C. (1997). – Mesure stratigraphique de la déformation: application à l'évolution jurassique du bassin de Paris. – *Mém. Géosciences-Rennes*, **77**, 293 p.

ROBIN C., ALLEMAND P., BUROV E., DOIN M. P., GUILLOCHEAU F., DROMART G. & GARCIA J.-P. (2003). – Vertical movements of the Paris Basin (Triassic – Pleistocene): from 3D stratigraphic database to numerical models. *In*: D.A. NIEUWLAND, Ed., New insights into structural interpretation and modelling. – *Geol. Soc., London, Sp. Publ.*, **212**, 225-250.

ROUSSELLE B. (1997). – Partition stratigraphique des faciès et des volumes de dépôt en domaine de plate-forme carbonatée: l'exemple dans l'aalénien du Sud-Est de la France. – *Doc. CST Lyon*, **143**, p. 225.

RUFFELL A., MCKINLEY J. M. & WORDEN R. H. (2002). – Comparison of Clay mineral stratigraphy to other proxy palaeoclimate indicators in the Mesozoic of NW Europe. – *Phil. Trans. R. Soc. Lond. A.*, **360**, 675-693.

SIMKEVICIUS P., AHLBERG A. & GRIGELIS A. (2003). – Jurassic smectite and kaolinite trends of the East European Platform: implications for palaeobathymetry and palaeoclimate. – *Terra Nova,* **15,** (4), 225-229.

SOUSSI M. (2003). – Nouvelle nomenclature lithostratigraphique " événementielle " pour le Jurassique de la Tunisie atlasique. – *Geobios*, **36**, 6, 627-792.

STRASSER A. (1986). – Ooids in Purbeck limestones (lowermost Cretaceous) of the Swiss and French Jura. – *Sedimentology*, **33**, 711-727.

THIRY-BASTIEN P. (2002). – Stratigraphie séquentielle des calcaires bajociens de l'Est de la France (Jura et bassin de Paris). – Doctoral thesis, Université de Lyon, France, 378 p.

UNDERHILL J.R. & PARTINGTON M.A. (1993). – Use of genetic sequence stratigraphy in defining and determining a regional tectonic control on the "Mid-Cimmerian Unconformity": implication for North Sea basin development and the Sea-Level Chart. *In*: P. WEIMER & H. POSAMENTIER, Eds., Siliciclastic sequence stratigraphy. – *AAPG*, **58**, 449-484.

VAIL P.R., AUDEMARD F., BOUMAN S.A, EISNER P.N. & PEREZ-CRUZ C. (1991). – Stratigraphic signatures of tectonics and eustasy and sedimentology – an overview. *In*: G. EINSELE, W. RICKEN & A. SEILACHER, Eds., Cycles and events in stratigraphy. – Springer Verlag, Berlin, 671-659.

VASLET D., LE METOUR J. & LE NINDRE Y.-M. (2000). – Evénements au passage Lias-Dogger au Moyen-Orient. – *Strata*, (1), **10**, 1 fig., 70-73.

WANG Y., JIANG D., YANG H. & SUN F. (1997). – Middle Jurassic palynoflora and its paleoenvironmental implication in Turpan Basin, Xinjiang. – *Acta Sedimentol. Sinica*, **15**, 3, 133-140.

WANG Y., MOSBRUGGER V. & ZHANG H. (2005). – Early to middle Jurassic vegetation and climate events in the Qaidam Basin, Northwest China. – *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **224**, 200-216.

WETZEL A., ALLENBACH R. & ALLIA V. (2003). – Reactivated basement structures affecting the sedimentary facies in tectonically "quiescent" epicontinental basin: an example from NW Switzerland. – *Sediment. Geol.*, **157**, 153-172.

ZIEGLER P.A. (1982). – Geological atlas of western and central Europe. – *Shell Internat. Petrol. Maatschappij* B.V., Elsevier, **1**, p. 130

ZIEGLER P.A. (1988). – Evolution of the Arctic-North Atlantic and the western Tethys. – *Amer. Assoc Petrol. Geol.,* **43**, p. 198.