

Environmental changes around the Oligocene/Miocene boundary in the Limagne graben, Massif Central, France

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Abstract – Continental environments are very sensitive to climatic variations. A unique opportunity to study the climate changes where this stage boundary is well constrained by fossils. Indeed, some localities of the Limagne Graben Basin are so rich in mammal remains that they have become a European reference for mammal biostratigraphy. The dominant sedimentary facies of the lacustrine deposits in the northern part of the Limagne Graben Basin are composed of poorly cemented marls and calcarenites containing various plants and animals remains (*e.g.* algae, fish bones and teeth, gastropods, ostracods, mammals, birds and reptiles remains) associated with stromatolites. Mammal remains, well described in this area from the literature, were used to constrain the chronostratigraphic context of this lacustrine basin, with refinement thanks to new carbon and oxygen isotope measurements, palynological and sedimentological data. In this work, the available information obtained from a classical paleoecological study has been refined by new carbon and oxygen isotope analyses of carbonates and fish teeth retrieved from the washed sediment residues. The results of this study confirm that the Oligocene/Miocene boundary in Europe was a general period of aridity, associated with a cooler climate, which could be the cause of the decline in mammal paleodiversity observed during this period. The gradual evolution from brackish to fresh waters is indicated by the presence of ostracods and gastropods, and the major development of caddisflies. This period is associated to humid climatic conditions while a gradual increase in temperature took place throughout the second part of the Aquitanian. These environmental changes were driven by strong variations of temperatures and a contrasted seasonality.

Keywords: Oligocene/Miocene boundary / Limagne Basin / lacustrine carbonate / biozone / oxygen isotopes / apatite / stromatolite

Résumé – **Changements environnementaux survenant à la limite Oligocène/Miocène du bassin des Limagnes (Massif central, France).** Les environnements continentaux sont très sensibles aux variations climatiques. Une opportunité unique d'étudier les variations climatiques intervenant autour de la limite oligo-miocène est fournie par le bassin des Limagnes, car cette limite y est bien identifiée par les fossiles. En effet, certaines localités du bassin sont si riches en restes de mammifères qu'elles sont devenues des références pour la biostratigraphie mammalienne européenne. Les différents faciès sédimentaires présents dans les dépôts lacustres de la partie nord du bassin sont peu indurés. Il s'agit de marnes et de calcarénites qui ont livré de nombreux fossiles de plantes et d'animaux (algues, restes de poissons, gastéropodes, ostracodes, mammifères, oiseaux et reptiles), associés à des stromatolites. Les mammifères fossiles ont été utilisés par le passé pour contraindre le contexte chronostratigraphique du bassin lacustre ; ces données ont été affinées dans ce travail par une étude palynologique et sédimentologique. Les informations obtenues lors de cette étude paléocologique classique ont été complétées par l'analyse en isotopes stables des carbonates

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et des dents de poissons issues des lavages de sédiments. La présence d'une période d'aridité probablement à l'échelle de l'Europe à la limite oligo-miocène est confirmée par cette étude. Cette période d'aridité, associée à un climat plus froid, comme l'atteste la présence de pollens spécifiques, est probablement responsable de l'appauvrissement de la diversité mammalienne également observée durant cette période. Puis, le passage du milieu saumâtre à un milieu d'eau douce se met en place, à partir de l'Aquitainien, attesté par la présence d'ostracodes et de gastéropodes et le développement exceptionnel des phryganes (insectes Trichoptères). Ce passage est associé à des conditions climatiques de nouveau plus humides. La température, quant à elle, augmente graduellement dans la seconde partie de l'Aquitainien. Ces changements environnementaux ont eu lieu sous un climat à fortes variations de températures et une saisonnalité contrastée.

Mots clés : limite oligo-miocène / bassin des Limagnes / carbonates lacustres / biozone / isotopes de l'oxygène / apatite / stromatolite

1 Introduction

Recent advances made in defining the evolution of global climate during the Cenozoic (Zachos *et al.*, 2001) showed that a warming trend during the Late Oligocene reduced the extent of the Antarctic ice cap. Apart from a few events of glacial stages, the global volume of ice remained low until the Middle Miocene, along with a slight increase in bottom water temperature. One of these glacial events, referred as glacial maximum, occurred at the Oligocene/Miocene boundary as documented by Zachos *et al.* (2001). The present study focuses on this short-lived event and its consequences, in a region that was particularly sensitive to climate change: the continental environment of the Limagne Graben Basin located in the northern part of the Massif Central in France (Fig. 1). The lacustrine facies of this graben are particularly suitable for performing a detailed paleoclimatic study because of the exceptional density of paleontological remains (especially mammals) that enables a valuable dating of the sedimentary deposits. This manuscript reports on the main results of a multidisciplinary investigation of the “Limagne bourbonnaise” deposits at the Oligocene/Miocene boundary. To reconstruct past climate conditions, palynological, sedimentological and stable isotope analyses ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) of both carbonates (stromatolites and lacustrine limestone) and phosphates (fish teeth) have been performed.

2 Geological setting

The Limagne Graben Basin consists of several N-S-trending grabens in the northern part of the Massif Central in France and forms a part of the European Cenozoic Rift System (Maury and Varet, 1980; Ziegler, 1990; Merle *et al.*, 1998; Michon, 2000; Dèzes *et al.*, 2004). The northern part of the basin is known as the “Limagne bourbonnaise”, the central part as the “Limagne centrale” or “Grande Limagne”, and the southern part as the “Limagne d'Issoire” and “Limagne de Brioude” (Fig. 1). Associated with rapid Oligocene subsidence, this structural heritage greatly influenced the sedimentary infill of the basin, which is as much as 2000 m thick in the “Limagne centrale” (Grolier and Tchimichkian, 1963; Morange *et al.*, 1971; Gorin, 1975; Donsimoni and Giot, 1977). In the “Limagne bourbonnaise”, the older sedimentary deposits are Late Lutetian in the eastern part of the basin and Bartonian in the western part (*e.g.* Late Eocene in age) (Riveline *et al.*,

1988). The Rupelian (Early Oligocene) lacustrine sediments were preserved in the “Limagne centrale”, “Limagne d'Issoire” and “Limagne bourbonnaise” (Guillot, 1991) and reflect a brackish environment characterized by the presence of gastropods (*Potamides lamarckii*) and coccoliths locally associated with evaporites.

During the Chattian period (Upper Oligocene), a fluvial supply from the north is observed (Wattinne, 2004). The lake at this time was well developed, as testified by the presence of stromatolites in contact with the basement around the basin edges. Nevertheless, a retreat of the shoreline is indicated at the end of the Chattian by the development of numerous paleosols (for more details see Roche *et al.*, 2018).

During the Aquitanian (Early Miocene), the lacustrine domain was mainly restricted to the northern part of the basin (Limagne bourbonnaise; Fig. 2) with fluvial supplies coming from the east (Wattinne, 2004). The western part is characterized by a narrow basin (Fig. 2) filled with Miocene sediments. It is interpreted as an ancient stream that later migrated eastward (Huguency *et al.*, 1999) to become the present-day Allier River (Fig. 1). The Aquitanian, marking the last lacustrine episode recorded by the sedimentary deposits filling in the graben, was followed by the development of Burdigalian (Early Miocene) fluvial systems. These deposits are characterized by marls and sandstones with feldspars and silex (Jung, 1946; Bout *et al.*, 1966; Jeambrun *et al.*, 1973; Giot *et al.*, 1979) then are followed by the Pliocene “sand and clays of the Bourbonnais” formation (Tourenq, 1989).

The overall lacustrine sedimentary record of the Limagne Graben Basin is characterized by an alternation of marls and calcarenites associated with stromatolites showing various morphologies (Donsimoni, 1975; Freytet, 2000; Wattinne *et al.*, 2003) and abundant mammal remains.

Some localities in the Limagne graben are so rich in mammal remains that they became reference levels for the European Standard Mammal Biozonation. For example, the faunal content documented in Coderet is used as the reference to define MP 30 (the last level of the Paleogene, referred to as MP) and in Montaigu-le-Blin to define MN2 (the Neogene referred to as MN; Fig. 3). Other mammal localities record the same associations at the Oligocene/Miocene boundary (Huguency, 1997).

The general persistence of Late Oligocene lineages and the pattern of change being roughly the same throughout Europe suggests that the faunas of the earliest Miocene derived from an impoverished Oligocene assemblage. That is why the position of the Oligocene/Miocene boundary, in terms of

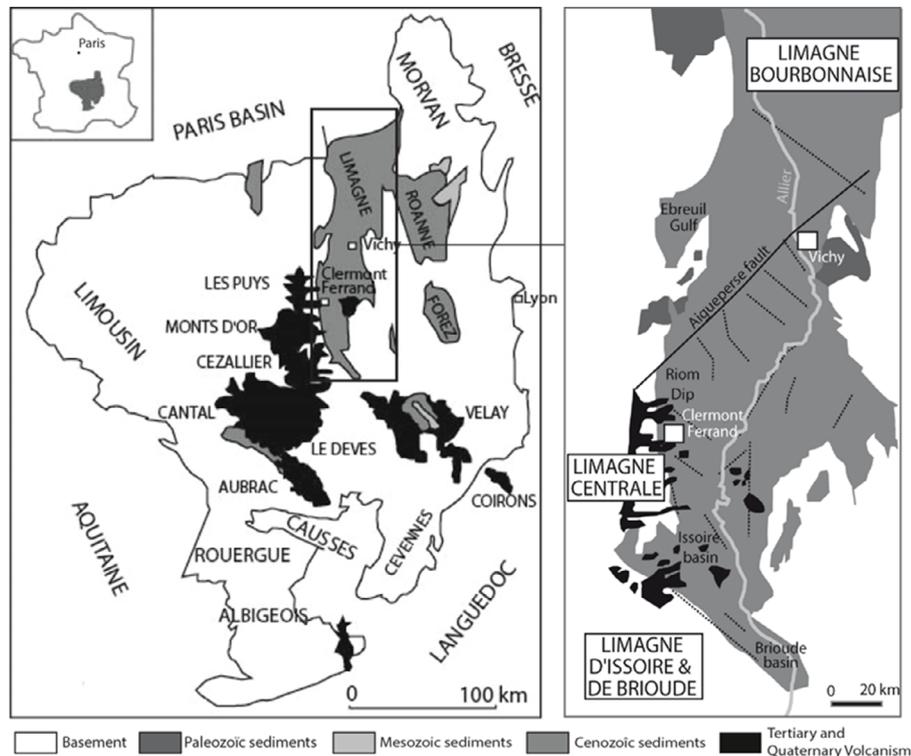


Fig. 1. The Massif Central area, from Roques (1971) and regional sketch map of the Limagne Graben (from COGEMA, in Massoubre, 1986).

mammalian faunas, was debated (Harland *et al.*, 1982; Cavalier and Pomerol, 1983; Odin, 1994; Berggren *et al.*, 1995; Odin *et al.*, 1997; Ginsburg *et al.*, 1998).

The base of the Neogene is fixed at 23.8 Ma (Huguency *et al.*, 2003) which is also the base of chron C6 Cn.2n (Fig. 3). The Créchy 1-2 level is well correlated with Brochene Fluch 53 (Switzerland) which is estimated as Oligocene by Picot (2002).

These layers are slightly older than Coderet (MP30). The Late Oligocene faunas of Limagne are generally diverse and abundant. The Gannat fauna yielded 13 families and 16 species of which only five are rodents (Fig. 2). The same faunal pattern is recognized in other Limagne localities such as La Roche-Blanche/Gergovie (Huguency *et al.*, 1999) and Cluzel, and also in Rottenbuch 8 (Germany) (Fahlbusch and Heissig, 1987) and Boudry 2 (Switzerland) (Engesser and Mödden, 1997).

A preliminary overview of the mammal data highlights the location of the Oligocene/Miocene sedimentary boundary in the basin (Fig. 2).

The mammal sites were investigated more specifically in the eastern part of the basin (Créchy, Montaigu-Le-Blin, Gondailly, Chavroches), the Oligocene/Miocene boundary being particularly well exposed at the Créchy site (Huguency *et al.*, 2003).

3 Material and methods

Samples were collected from different quarries (172 samples from Montaigu-le-Blin; 204 samples from Créchy; 13 samples from Gannat). All layers of the studied sections were sampled and systematically washed to identify the coarse

components (see Figs. 4, 5A and 5B, for an example of section sampling).

The samples were sieved through 1.0 mm, 0.5 mm, 0.250 mm, 0.125 mm, 63 μm , and 25 μm mesh sizes to remove the finer clay phase and to allow the coarser components to be identified (specifically floral and faunal contents), which were then sorted and counted in a semi-quantitative way, with the quantitative abacus proposed by Terry and Chilingar (1955).

Nineteen selected samples were sent to the BRGM laboratory in Orléans, France, to extract the palynomorphs (see Wattinne (2004) for the protocol used). Only four of these samples yielded microflora.

Oxygen isotope ratios of fish tooth phosphate are now considered as reliable low-temperature paleothermometers (Tudge, 1960; Kolodny *et al.*, 1983; Shemesh *et al.*, 1988; Lécuyer *et al.*, 2013). It is widely considered that the oxygen isotope composition of fish teeth provides both water temperature and isotopic composition when the fish was alive and that this record is preserved after death. Oxygen isotope analyses were performed on fossil fish remains sampled from the Créchy and Montaigu-le-Blin quarries. The studied fossiliferous fish beds show a monospecific assemblage of Cyprinidae (*Tarsichthys* sp. TROSCHEL determined by J. Gaudant). The teeth were isolated through a simple washing of the sediment, then extracted and crushed for isotope analysis. About 30 teeth were pooled per sample, which represents a weight ranging from 15 to 30 mg. Sediment layers delivering more than 30 teeth (fossiliferous fish beds) were relatively scarce and were sufficient for only seven analyses (labelled here as layer a to g). Seven additional analyses were performed on teeth collected from contiguous layers (labelled here as

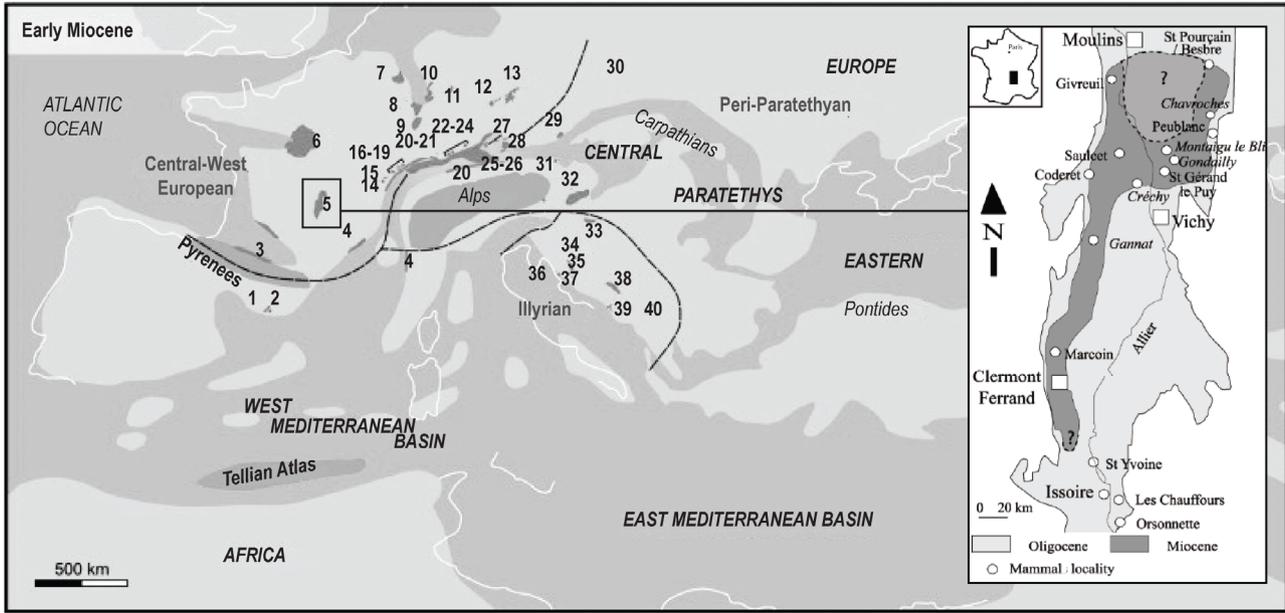


Fig. 2. Palinspastic map for the Early Miocene with indication of palaeobiogeographic units (from Neubauer *et al.*, 2015, modified after Popov *et al.*, 2004 (<https://www.sciencedirect.com/science/article/pii/S0012825215000197#bb0525>)). Palaeogeography of the Upper Rhine Graben emended after Berger *et al.* (2005) (<https://www.sciencedirect.com/science/article/pii/S0012825215000197#bb0065>). Outlines are drawn after palaeogeographic reconstructions or sediment distributions. Faunas of freshwater systems fringing the Central Paratethys do not form a homogenous palaeogeographic entity. They are based on too many localities to be clearly indicated on the map. Abbreviations: 1 – Vallès-Penedès (m); 2 – Vilanova i la Geltrú (m); 3 – Aquitaine (m); 4 – Lower Rhône (m); 5 – Limagne (l); 6 – Paris (m); 7 – Lower Rhine (w); 8 – Mainz (b); 9 – Upper Rhine Graben (b); 10 – Hanau-Wetterau (b); 11 – Rhoen (l); 12 – Sokolov-Cheb (l); 13 – North Bohemian Lake (l); 14 – Sainte-Croix (l); 15 – Fleurier (b); 16 – Courtelary (b); 17 – Moutier (l); 18 – Delemont (b); 19 – Laufen (l); 20 – Upper Marine Molasse (m); 21 – Upper Marine Molasse (“Helicidenmergel”) (m); 22 – Öpfingen (l); 23 – Thalgingen (w); 24 – Oggenhausen (l); 25 – Upper Brackish Water Molasse (b); 26 – Upper Freshwater Molasse (w); 27 – Sandelzhausen (w); 28 – Bavarian Rzehakia (b); 29 – Moravian Rzehakia (b); 30 – Bełchatów (l); 31 – Korneuburg (f); 32 – Bakony (l); 33 – Mecsek (l); 34 – Glina (l); 35 – Bihać-Cazin (l); 36 – Pag (l); 37 – Udbina (l); 38 – Sarajevo (l); 39 – Mostar (l); 40 – Trijebine (l). Environments are characterised as: b – brackish; f – fluvatile; l – lacustrine; m – marginal marine; w – wetlands; u – unknown – Location of the Oligocene/Miocene boundary deduced from mammal sites in the Limagne graben (Hugueney *et al.*, 1999).

Magnetostratigraphic calibration		GERMANY/ SWITZERLAND /FRANCE (SAVOIE)	Mammal scale	LIMAGNE BASIN
MIOCENE	23 Ma	La Chaux	MN2a	MONTAIGU-LE-BLIN
		Fornant11	MN1	Upper part of Billy La Roche Blanche Gergovie section
	23,8 Ma	Rottenbuch 8 Boudry 2		Upper part of the Gannat section
OLIGOCENE	24 Ma	6Cn.1n 6Cn.1r 6Cn2n	6Cn2r	
		Brochen Fluch 53 Küttigen	MP30	CODERET Crechy 1-2 section
		Brochen Fluch 19/20 Rickenback	MP29	Lower part of the Crechy section

Fig. 3. Mammal localities around the Oligocene-Miocene boundary; the reference localities of the mammal reference scale are in capital letters. Localities calibrated by magnetostratigraphy (bold type) are indicated with their error limits. Brochene Fluch 53 (MP30), is dated from 23.7 to 24.1. Pluridisciplinary analysis of the Brochene Fluch section makes possible the definitive assignment of the Brochene Fluch 53 locality to the Late Oligocene (N.B. in the paper by Becker *et al.* (2002): the base of the Aquitanian and the corresponding magnetostratigraphy) was erroneously placed in MP 30. It should be placed in level 58 of the section, see Picot (2002).

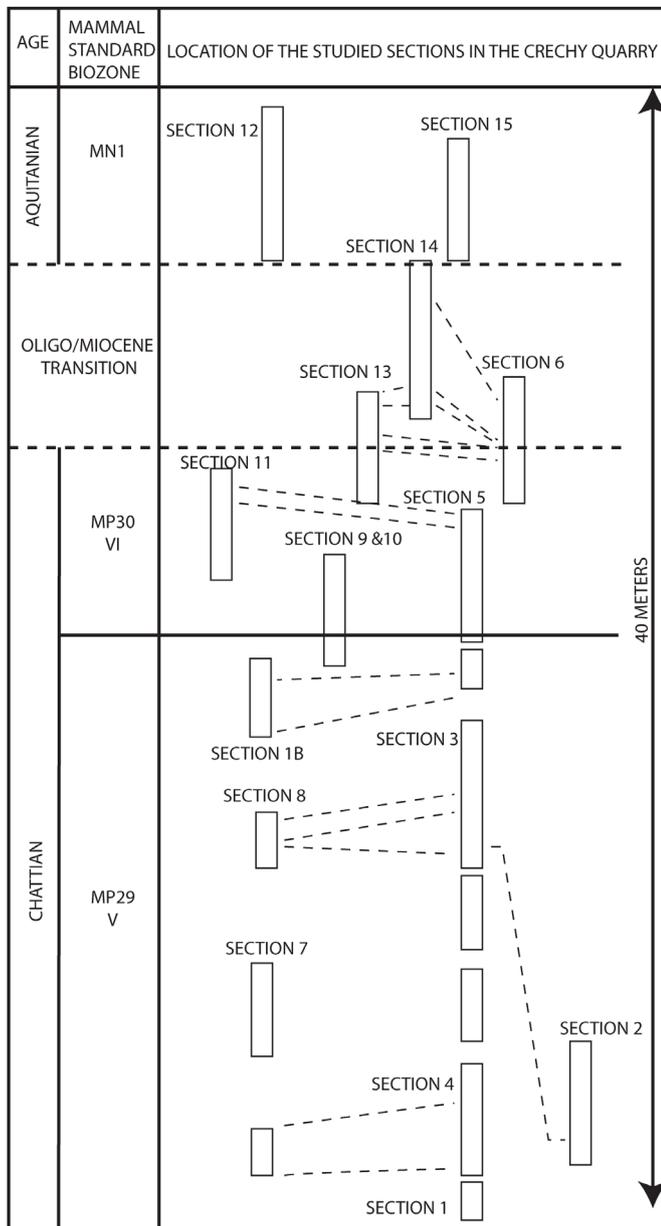


Fig. 4. Location of the studied sections in the Créchy quarry and corresponding biozones.

layers A to G) that is to say a mixture with teeth coming from different layers but attributed thanks to mammal rests and sedimentological study at the same period of time. This mixture of teeth samples was necessary to obtain the minimum weight required for a high-precision oxygen isotope analysis of the tooth apatite phosphate (Tab. 1). The isolation of phosphate radicals from the fish teeth was performed by precipitating Ag_3PO_4 crystals using a method developed by Crowson *et al.* (1991) and adapted by Lécuyer *et al.* (1993). The extraction and oxygen isotope analysis followed the method described by O'Neil *et al.* (1994) and modified by Lécuyer *et al.* (1998).

For the phosphates, we used the following isotopic fractionation equation (Lécuyer *et al.*, 2013):

$$T(^{\circ}\text{C}) = 117.4 - 4.50(\delta^{18}\text{O}_p - \delta^{18}\text{O}_w) \quad \text{with } \delta^{18}\text{O}_p = \delta^{18}\text{O} \text{ value of the phosphate (\% VSMOW)} \text{ and } \delta^{18}\text{O}_w = \delta^{18}\text{O} \text{ value of water (\% VSMOW)}.$$

Four samples of lacustrine limestones were selected from the fossiliferous fish beds (3 from Créchy, 1 from Montaigu-le-Blin) in order to compare their $\delta^{18}\text{O}$ values with those obtained from the fish teeth. The analyses were performed with a Finnigan Delta E isotopic ratio mass spectrometer at the Laboratoire de Géologie de Lyon.

Thin sections for petrographic analyses were made on 10 stromatolite samples and studied under optical transmitted light and cathodoluminescence; the latter technique revealed the internal structure of the stromatolite and locally the presence of diagenetic alteration. In addition, 42 laminations of a stromatolite from Créchy (10 cm high; CRE-1) were sampled with a microdrill core system in order to characterize the isotopic variations recorded during its growth.

Finally, five selected stromatolites (around 10 cm high) from Créchy, Gannat, Chavroches and Montaigu-le-Blin were powdered and analysed in bulk in order to characterize the global isotopic variations recorded in their structure through the Chattian/Aquitanian boundary.

For the carbonates we used (Anderson and Arthur, 1983) isotopic fractionation equation:

$$T(^{\circ}\text{C}) = 16.9 - 4.2(\delta^{18}\text{O}_{\text{Ocalcite}} - \delta^{18}\text{O}_{\text{Owater}}) + 0.13$$

($\delta^{18}\text{O}_{\text{Ocalcite}}$ – $\delta^{18}\text{O}_{\text{Owater}}$) (PDB).

The VSMOW/PDB transition can be calculated from the Coplen *et al.* (1983) equation:

$$\delta^{18}\text{O}(\text{PDB}) = 0.97002 \times \delta^{18}\text{O}(\text{SMOW}) - 29.98.$$

The use of these equations requires an estimate of the water $\delta^{18}\text{O}$ value, which can be obtained using the Bowen and Wilkinson (2002) equation:

$$\delta^{18}\text{O}(\text{VSMOW}) \text{ of the lake water} = -0.0051 \text{ Lat}^2 + 0.1805 \text{ Lat} - 0.002 \text{ Alt} - 5.247,$$

Lat = latitude of the studied site;

Alt = altitude of the studied site.

5 Pollen microflora around the Oligocene/Miocene boundary

5.1 Pollen data in Limagne compared with adjacent area

A set of 20 samples was selected from the open quarries of the Limagne basin for palynological analysis. Most of them were barren of microflora. Nevertheless, four samples from Créchy-Bas (MP29) and Montaigu-le-Blin (MN2a) quarries yielded spores and pollen grains (Tab. 2).

The vegetal communities were mainly composed of coniferal forest elements (including *Tsuga*, *Abies* and *Picea* taxa) and subsequently of deciduous forest taxa represented by *Betulaceae*, *Ulmaceae*, *Corylaceae*, *Fagaceae*, *Juglandaceae*, *Oleaceae* families. Mega-mesotherms specimens are poorly represented. Nevertheless, the discrepancies highlighted elsewhere between the Chattian and Aquitanian floras (Hochuli, 1979, 1984; Guinet, 1984; Chateaufort and Nury 1995) also exist in the studied area. The disappearance of *Tsuga* pollen is observed in the upper part of the Chattian sequence and an increase of *Euphorbiaceae*-*Juglandaceae* is pinpointed at the base of Aquitanian.

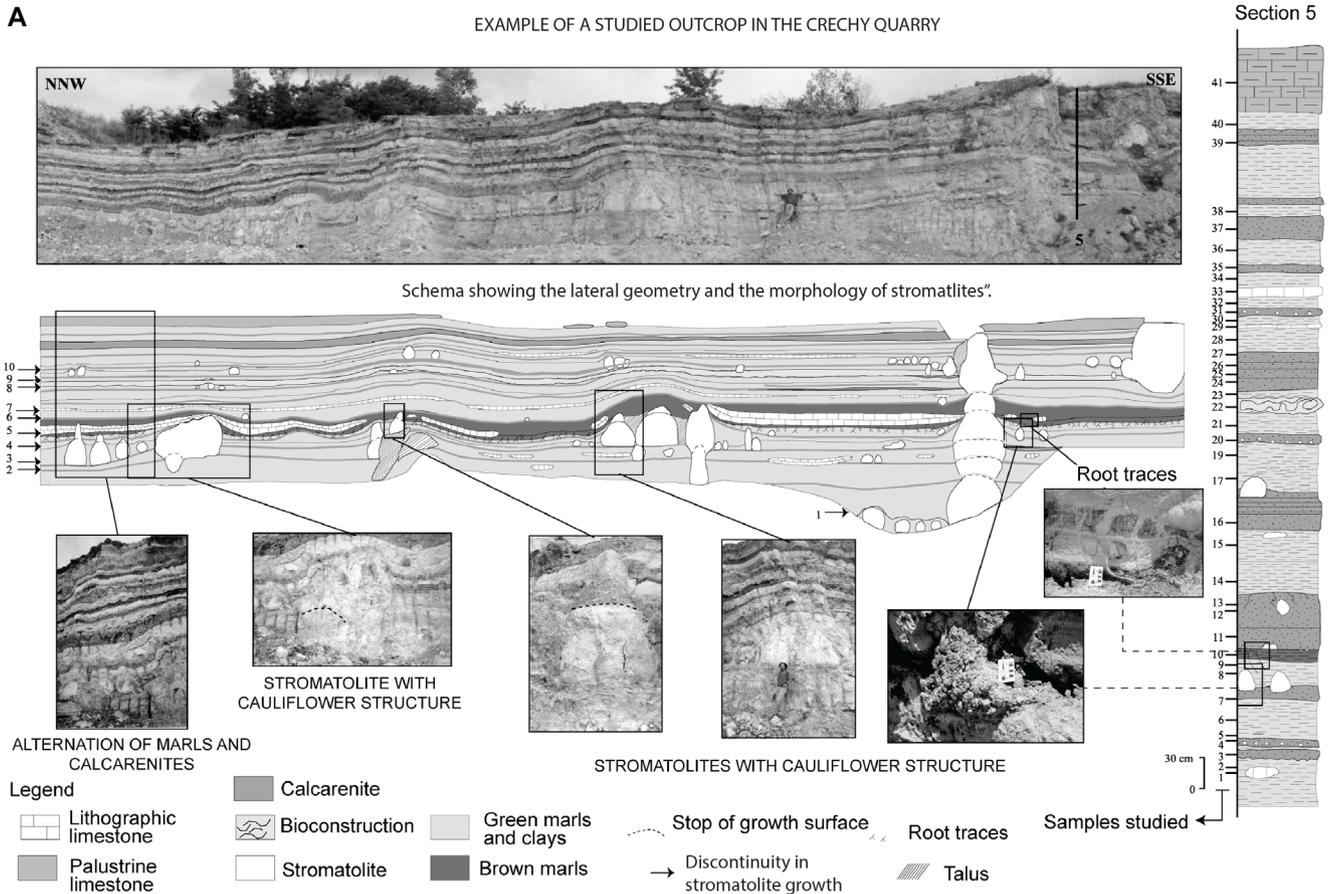


Fig. 5. A. Example of the sedimentological context of the Créchy quarry; detail of Section 5 and sampled layers. B. Example of the different coarse components (%vol. of the residues) present in the washed sediments of Section 5 (see Figs. 4 and 6 for location) in the Créchy quarry.

Correlations of corresponding associations with the Monbrison basin (Schuler and Sittler, 1969, 1976; Gorin, 1975) or the Provence basin (Bessedik, 1985; Chateaufeuf and Nury, 1995) are difficult, due to scarcity and discontinuity of sampling in the Limagne basin area. However, the Créchy-Bas microflora, well dated by mammals (MP29), can be compared with the Provence basins. In the Provence basin, the microflora content at the Chattian-Aquitainian transition has been well documented: a cool dry phase took place during the upper part of the Chattian, but the following Aquitainian climatic changes still need to be better defined (Bessedik, 1985; Chateaufeuf and Nury 1995; Nury, 1988; Nury *et al.*, 2016), (Bessedik, 1985, Huguency and Truc, 1976; Huguency *et al.*, 1999; Escarguel and Aguilar, 1997; Neubauer *et al.*, 2015).

6 Sedimentology and associated faunal content

Sections in the Créchy, Montaigu-le-Blin, Gannat and Gondailly quarries were studied in detail for facies analysis. Four major depositional environments have been proposed (Wattinne, 2004):

- a fluvial domain, characterized by channels infilled by quartz and calcarenite pebbles, conglomerates and sands composed of quartz and locally heavy minerals;

- a proximal lacustrine domain characterized by non-cemented calcarenites composed of oncolites, oolites, ostracods, gastropods, fish remains, algal debris and caddisflies, all of them being deposited in a shallow-water environment favourable to stromatolite growth;
- a deeper eutrophic lacustrine zone characterized by wackestones, micropackstones, green marls, and bioaccumulations of ostracods or gastropods;
- a palustrine zone, leading sometimes to protosols with root traces and mudcracks, associated with terrestrial fauna (birds bones, eggshell fragments, mammal remains).

Several repetitive centimetric sequences characterized by alternations of stromatolite-bearing calcarenites and clayey layers have been observed. Most of the clayey layers were halting the growth of the underlying stromatolites. The clayey layers deposits are interpreted as changes in the climatic conditions, with a more arid climate leading to eutrophic conditions.

The Oligocene and Miocene sedimentary deposits contain lacustrine faunal and floral associations which vary in terms of relative abundance around the Oligocene/Miocene boundary. The main faunal and floral assemblages have already been described in the Créchy quarry (Huguency *et al.*, 2003).

The Oligocene deposits (calcarenites and marls) are dominated by ostracods (Créchy, Gannat) with rare gastropods

B

Sample	Facies	% of residues										
		Detrital minerals	Oncolites	Faunal rests			Caddisflies	Gastropods			Ostracods	Algal debris
				Eggs	Fish	Bones		Valvata	Pseudamnicola	Helicidae		
40	Clayey calcarenite	8	42	0	14	0	0	0	14	0	14	8
39	Clayey calcarenite	8	60	6	8	3	0	0	3	0	9	3
38	Green marl	8	65	0	13	0	0	0	3	0	8	3
37	Fine calcarenite	11	57	0	14	0	0	0	15	0	3	0
36	Green marl	12	52	0	12	0	0	0	2	0	19	3
35	Brown marl	8	54	0	38	0	0	0	0	0	0	0
34	Green marl	8	70	0	10	0	0	0	0	0	12	0
32	Green marl	15	60	0	5	0	0	0	5	0	5	13
31	Coarse calcarenite	6	60	0	15	0	0	0	8	0	4	7
30	Green marl	8	70	0	0	0	0	0	0	0	10	13
29	Beige marl	8	82	0	0	0	0	0	0	0	5	5
28	Green marl	8	67	0	24	0	0	0	0	0	1	0
27	Fine calcarenite	9	58	0	15	0	0	0	10	0	3	5
26	Coarse calcarenite	12	53	0	1	0	0	0	8	0	10	16
25	Bioclastic calcarenite	15	53	2	0	0	0	0	12	0	9	9
24	Bioclastic calcarenite	8	74	0	0	2	0	0	4	0	0	10
23	Green marl	4	77	0	0	0	0	0	0	0	3	16
21	Brown marl	8	59	0	25	0	0	0	0	0	0	8
20	Clayey calcarenite	8	80	0	8	0	0	0	2	0	2	0
19	Green marl	10	72	0	8	0	0	0	0	0	5	5
17	Green marl	8	63	0	27	0	0	0	2	0	0	0
14	Green marl	15	55	0	30	0	0	0	0	0	0	0
12	Clayey calcarenite	4	45	0	12	0	3	0	16	0	8	12
11	Brown marl	10	70	0	0	1	1	0	0	0	3	15
10	Brown marl	17	56	0	0	0	0	0	0	0	25	2
8	Green marl	5	62	0	8	0	0	0	0	0	20	5
7	Calcarenite	18	40	0	0	0	5	0	19	0	13	5
6	Green marl	5	12	0	0	0	0	0	0	0	81	2
5	Green marl	7	8	0	85	0	0	0	0	0	0	0
4	Fine calcarenite	8	82	0	0	0	0	0	0	0	5	5
3	Calcarenite	5	72	0	5	0	0	0	3	0	5	10
2	Brown/green marl	6	61	0	15	0	0	0	2	0	8	8

Fig. 5. (Suite)

Table 1. Location and corresponding biozones of the three types of samples selected for the stable isotope analysis.

Age	Biozone	Type of sample		
		Fish teeth beds	Lacustrine limestone (nodules)	Stromatolite
Aquitanian	MN2a	H – Montaigu-le-Blin	(4)-MLB	Montaigu-le-Blin (MLB) Chavroches (CHA)
		G – Montaigu-le-Blin		
Oligocene/Miocene boundary	MP30/MN1	F-Créchy f-Créchy	(3)-CRE	Créchy (CRE 3)
Chartian	MP30 VI	E-e – Créchy	(2)-CRE	Gannat (GAN) Créchy (CRE 2)
		D-d – Créchy		
		C-Créchy		
	B-c Créchy	(1)-CRE		
	MP29 V	A-a/b Créchy		Créchy (CRE 1)

Table 2. Number of spore and pollen grains identified in the samples of the Créchy and Montaigu-le-Blin quarries.

Localisation Samples	Crechy route		Montaigu-le-Blin	
	Cr. 28724	Cr. 28716	Mon. 28709	Mon. 5680
Pinaceae (Pinus diploxylon type)	40	75	80	80
Pinaceae (G. Cathaya)	5	5	X	10
Pinaceae (G. Abies)	8	2	X	
Pinaceae (G. Picea)	1	X	X	2
Pinaceae (G. Tsuga)	1			
Pinaceae (G. Cedrus)	5			2
Podocarpaceae (Podocarpus)	1			2
Ulmaceae (Ulmus/Zelkova)	2		X	
Betulaceae (G. Alnus)	1			
Betulaceae (G. indéterminé)	3	X	X	
Corylaceae (G.Corylus)	X			
Fagaceae (G. Quercus)			2	
Betulaceae (G. Carpinus)	X			
Myricaceae (G. Myrica)	X	X		
Juglandaceae (Carya simplex type)	2	2	X	
Juglandaceae (G.Pterocarya/Platycaria)	X			
Juglandaceae (other genus)	X	X	2	
Cupressaceae / Taxodiaceae	2	2	X	
Caprifoliaceae				X
Oleaceae	1	2		
Ericaceae	X		X	
Chenopodiaceae		X	X	
Graminae	5			
Ephedraceae (G. Ephedra)	X			
Olacaceae	X	X	X	
Cycadaceae		5		
Eleagnaceae (Slow. Hippophaeoides)		X		
Euphorbiaceae (G. Phyllanthus)			X	
Araliaceae (G. Ilex)			X	
Ferns spore (varied genus)	X			
Lacustrine inaperturate	18			
Undetermined pollen	2		3	3
Reworked pollen			?	
Age (mammals zones)	Chattian (MP29)		Aquitanian (MN2a)	

(*Bithinella arvernensis* BOUILLET = *Pseudamnicola arvernensis* REY) indicative of a fresh-water environment. The abundance of fish remains at the end of Oligocene is interpreted as successive thanatocœnoses formed during dry periods (Hugueneu *et al.*, 2003). Moreover, at the end of the Oligocene, a major development of palustrine facies leading to protosols has been observed. Root traces, mudcracks and fossil bird remains indicate a retreat of the shoreline. Associated faunal content show specific gastropods (*Hydrobia* sp.), which are indicative of a brackish water environment at Créchy (P. Lozouet, pers.com.), (Fig. 6).

The Miocene deposits (MN1, MN2) are mostly characterized by calcarenites associated with stromatolites, caddisflies, gastropods and ostracods (Fig. 6). The most abundant lacustrine gastropods are *Valvata* sp. and *Pseudamnicola arvernensis*, which are usually found in a fresh-water environment (Créchy, Montaigu-le-Blin, Gondailly). All these variations in fauna content are interpreted as resulting from salinity variations in response to a drier event at the Oligocene/Miocene boundary.

The shallow-water lacustrine environment was very sensitive to climate changes and the alternance of palustrine and lacustrine facies through time is interpreted as reflecting changes in the paleo-lake levels that may be linked to rainfall fluctuations associated with a marked seasonality.

7 Stable oxygen isotope analysis

7.1 Stable isotope analysis of bulk stromatolites

The stromatolites located in the calcarenite levels grew preferentially during wet periods (Wattinne *et al.*, 2003). The data (Tab. 3) show that Aquitanian stromatolites have higher $\delta^{18}\text{O}$ values (-0.4 ; -0.1) than Chattian stromatolites (-2.9 to -1.6). Mammal remains (Hugueneu, pers com) indicate that Chavroches deposits are older than the Montaigu-le-Blin ones despite their belonging to the same biozones. At the same time, the Chattian stromatolites have negative to slightly positive $\delta^{13}\text{C}$ values (-3.2 to 1.5) whereas Aquitanian stromatolites

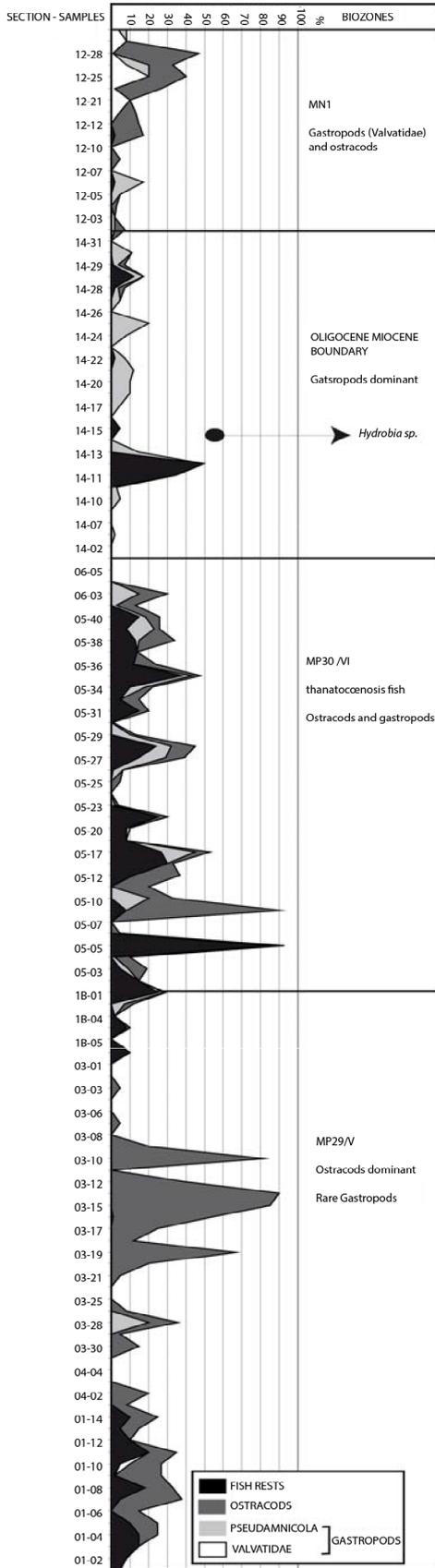


Fig. 6. Distribution of ostracods, fish teeth and gastropods in the Créchy quarry.

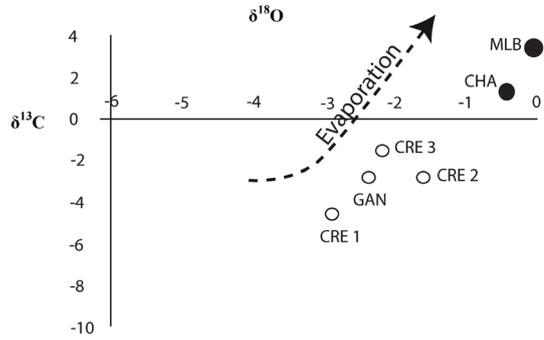


Fig. 7. Position of the studied stromatolites in a $\delta^{18}\text{O}$ – $\delta^{13}\text{C}$ space. The Aquitanian samples (Chavroches, Montaignu-le-Blin, **black points**) seem to indicate different environments with an overall increase in evaporation.

have high positive $\delta^{13}\text{C}$ values (1.3; 3.3). The $\delta^{18}\text{O}$ values increase with increasing evaporation while the photosynthetic activity associated with water evaporation also leads to increase in the $\delta^{13}\text{C}$ values of the precipitated carbonate (Casanova and Hillaire-Marcel, 1992, 1993; Andrews *et al.*, 1993, 1997; Arenas *et al.*, 1993, 1997; Zamarreño *et al.*, 1997). As these stromatolites are well dated by sedimentary deposits, we can observe a general trend in the lake with a gradual increase of water evaporation associated with higher photosynthetic activity (Fig. 7).

7.2 Detailed isotopic study of the Créchy stromatolites (CRE1)

$\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ variations in stromatolites primarily recorded changes in the environmental hydrological parameters throughout their growth (Casanova and Hillaire-Marcel, 1992, 1993; Andrews *et al.*, 1993, 1997; Arenas *et al.*, 1993, 1997; Zamarreño *et al.*, 1997). Stromatolite samples have negative $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values ($-6.5 < \delta^{13}\text{C} < -2.3$ and $-5.1 < \delta^{18}\text{O} < -1.6$; $n=42$, Tab. 4; Fig. 8).

Stromatolites from Créchy (CRE-1) show a positive correlation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values ($r=0.75$; Fig. 8), except for samples 24 and 27. The covariance between the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values is ascribable to the isotopic evolution of the water mass and indicates rather stable hydrological conditions (Talbot and Kelts, 1990), *i.e.* a closed lake where primary production is influenced by periods of either water dilution or concentration. This suggests that during the growth of stromatolites, the water of the lake had probably led to establishing an isotopic equilibrium between atmospheric CO_2 and the dissolved inorganic carbon (DIC) enhanced by photosynthetic activity. This process involves a ^{13}C enrichment of the water DIC due to the preferential use of the ^{12}C by the microbial community during photosynthetic activity (Rau, 1978; Herczeg and Faifbanks, 1987; Merz, 1992; Casanova and Hillaire-Marcel, 1993). Two periods are characterized by uncorrelated $\delta^{18}\text{O}$ (more negative) and $\delta^{13}\text{C}$ values (less negative) as revealed by samples 24 and 27 (Fig. 8). They indicate disturbances that affected the lake hydrology during the stromatolite growth. These disturbances could have various origins, such as a northward opening of the basin or a local

Table 3. Stable isotope data for stromatolites and nodules sampled at Créchy (CRE), Montaignu-le-Blin (MLB), Chavroches (CHA) and Gannat (GAN).

Age	Biozone	Stromatolite	$\delta^{18}\text{O}_{\text{PDB}}$	$\delta^{13}\text{C}_{\text{PDB}}$	Nodules	$\delta^{18}\text{O}_{\text{PDB}}$	$\delta^{13}\text{C}_{\text{PDB}}$
Aquitanian	MN2	MLB	-0.1	3.3	(4)-MLB	-4.5	-9.1
		CHA	-0.4	1.3			
Near the Chattian/Aquitanian boundary	MP30/MN1	CRE (3)	-2.2	1.5	(3)-CRE	-5.1	-4.5
Chattian	MP30	GAN	-2.4	-3.4	(2)-CRE	-4.5	-5.4
		CRE (2)	-1.6	-2.7	(1)-CRE	-4.3	-4.1
	MP29	CRE (1) (average)	-2.9	-4.2			

Table 4. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of the laminations sampled in the Créchy stromatolite (CRE 1).

Sample	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$	Sample	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$	Sample	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$
1	-6.23	-4.4	15	-4.93	-3.4	29	-3.50	-2.3
2	-5.10	-3.9	16	-4.43	-2.9	30	-3.56	-2.0
3	-4.83	-3.8	17	-4.14	-2.4	31	-3.83	-2.0
4	-4.39	-2.8	18	-4.44	-2.7	32	-6.54	-5.1
5	-5.20	-3.8	19	-4.42	-2.7	33	-5.11	-4.0
6	-4.44	-2.3	20	-4.67	-3.1	34	-2.30	-2.9
7	-4.21	-3.0	21	-4.46	-2.8	35	-3.70	-2.7
8	-4.06	-2.3	22	-4.10	-3.1	36	-4.41	-2.6
9	-3.70	-1.6	23	-3.70	-2.3	37	-2.90	-2.4
10	-4.63	-2.7	24	-3.17	-3.2	38	-2.52	-1.8
11	-4.59	-3.6	25	-3.86	-2.0	39	-3.73	-2.1
12	-5.10	-3.2	26	-3.57	-2.3	40	-3.38	-2.3
13	-4.50	-3.7	27	-2.99	-2.9	41	-3.5	-2.6
14	-4.70	-3.6	28	-3.53	-2.9	42	-3.82	-2.5

river input. Lastly, it can be seen that the least negative $\delta^{18}\text{O}$ values are invariably located at the “surface” levels present in the stromatolite. Studying these surface levels in thin section and by cathodoluminescence shows that they are affected by dissolution gulfs associated with early diagenesis. They are related to halts in the algal growth. The isotopic record is thus most likely related to an alternation of humid and dry periods changes recorded in the stromatolite structure. Observed isotopic patterns also highlight the discontinuous growth of the stromatolite as well as the gradual increasing rate of evaporation of the lake. The general trend of the isotopic signal is interpreted as a global drying of the area through time (Casanova and Hillaire-Marcel, 1992, 1993; Arenas *et al.*, 1993, 1997; Andrews *et al.*, 1993, 1997; Zamarreño *et al.*, 1997). As all the studied stromatolites recorded these periods of early diagenesis only at their surface levels, this observation allows the comparison of the average $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values between the various stromatolites.

7.3 Results for the Limagne fish teeth

If it is postulated that the elevation of the Chattian and Aquitanian lakes were close to sea level (Briot *et al.*, 2001), and applying the Bowen and Wilkinson (2002) equation to the isotopic results (Tab. 5), we obtain a $\delta^{18}\text{O}$ value of the lake water ranging from -5 to 0‰ (VSMOW). We emphasize that

this value is only an approximation and does not take into account the altitudinal variations of the paleo-landscape. Those equations applied to a fossil lake cannot provide water temperatures but rather their potential variations through time. Accordingly, the isotopic record is interpreted in terms of positive or negative offsets relative to an arbitrary and constant water $\delta^{18}\text{O}$ value (-3‰) during the periods of aridity. The $\delta^{18}\text{O}$ value of the lake water was controlled by its hydrological balance (drainage, precipitation, evaporation), although variations through time most likely resulted from changes in either air relative humidity, air temperature and wind velocity. Sedimentological analysis contributed to put limits on these uncertainties; for example, tenches live in an eutrophic medium characterized by clayey deposits and lacustrine limestones, which is an environment associated with arid climates, whereas stromatolites of the Limagne graben grew under rather wet conditions. Lacustrine limestones could have thus precipitated in the higher part of the water column due to the intense phytoplanktonic activity during periods of aridity. Samples of those limestones (Tab. 5) were selected in order to compare their $\delta^{18}\text{O}$ values with those obtained from the fish teeth supposedly related to the same period of aridity (Tab. 6). The results depend on whether the sample corresponds to a single or a mixed layer, with the calculated temperature offsets varying between -4 °C and +2 °C (Tab. 6).

Detail of CRE (1) sampled at the base of section 5 - Crechy Quarry / MP29

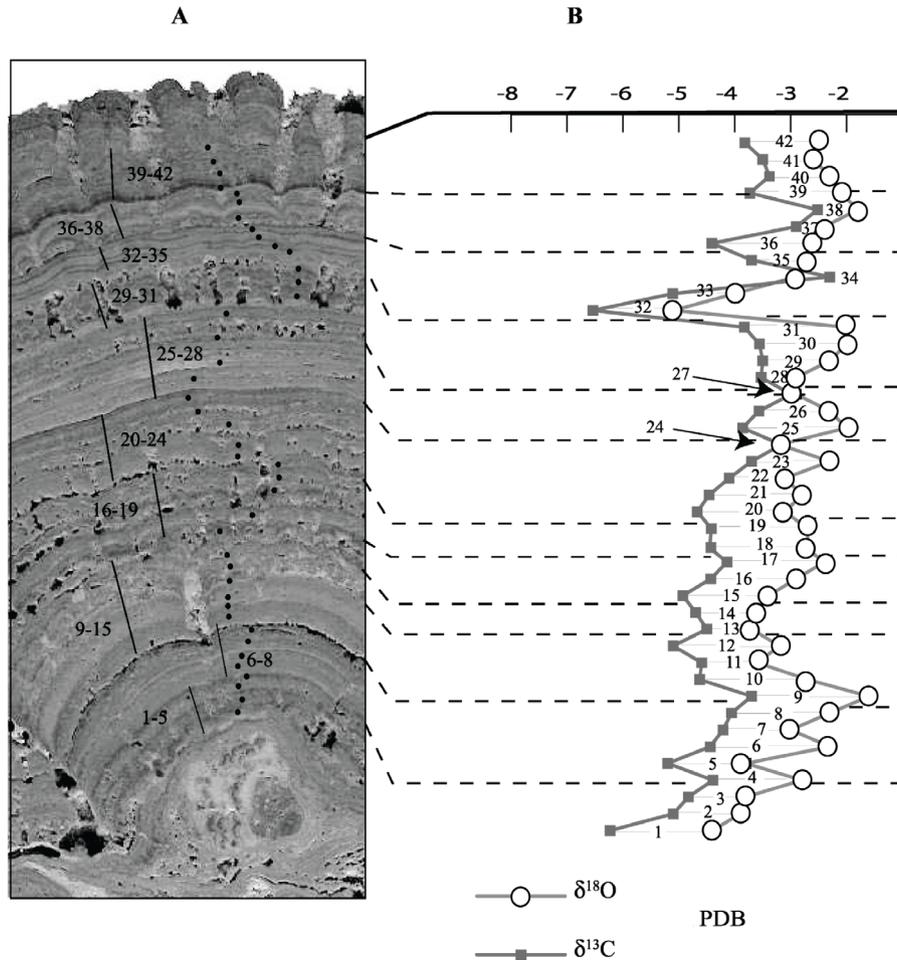


Fig. 8. A. Section of a stromatolite (CRE 1–10 cm high) showing the position of the sampled laminations. B. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of the stromatolite rings.

These results show that the temperature variations between the Chattian and the Aquitanian recorded by the fish teeth are related to a weak climatic warming during the Aquitanian period.

8 Climate evolution around the Oligocene/Miocene boundary

The Cr echy quarry shows a great variety of rodents preserved in the Late Oligocene beds, but also registers the Oligocene/Miocene transition with a drastic reduction of the fauna content and diversity at the beginning of the Neogene (Hugueney *et al.*, 2003). The basal Miocene impoverished faunas are dominated by eomyids and glirids and furthermore locally, zapodids. Later, the richness in species is greater as observed in Montaigu-le-Blin, which yielded an Early Miocene (MN2a) fauna characterized by 18 families and 33 species, but only 11 rodents. The faunal community indicates a more open tropical landscape. No younger fauna have been observed in the Limagne graben. Although episodes of appearance and disappearance took place in the Limagne

area during the Late Oligocene (MP29-30), the most drastic event took place at the MP30/MN1 boundary. Among the persistent lineages, new and more derived species developed at the Miocene base (Hugueney, 1997):

- at the family level, the entire Theridomyidae family, endemic to the European Late Eocene and Oligocene, disappeared;
- at the genus level, Cainotherium became the unique representative of the Cainotheriidae family, and Amphiperatherium of the Didelphidae family and Creodont Hyaenodon while the Artiodactyls Microbunodon and Anthracotherium disappeared. Neither the Eomyid Eomys nor the Cricetid Adelomyarion, Glirid Gliravus, and Castorid Rhizospalax crossed this boundary;
- at the species level, all the Oligocene species of Plesiosminthus disappeared and a single species, *P. myarion* appeared.

Legendre (1987, 1989) demonstrated that local extinctions in mammal faunas can be correlated with successive temperature decreases and that the more noticeable effect of a temperature drop is a decrease in the number of species

Table 5. Stable isotope data for lacustrine limestones at Créchy and Montaigu-le-Blin.

Age	Biozone	Nodules	$\delta^{18}\text{O}_{\text{PDB}}$	$\delta^{13}\text{C}_{\text{PDB}}$
Aquitanian	MN2	(4)-MLB	-4.5	-9.1
Chattian/ Aquitanian boundary	MP30/MN1	(3)-CRE	-5.1	-4.5
Chattian	MP30	(2)-CRE	-4.5	-5.4
		(1)-CRE	-4.3	-4.1
	MP29			

Table 6. Stable isotope data for fish teeth at Créchy and Montaigu-le-Blin. The calculated temperature offsets were based on the value given by the preceding layers for a constant water $\delta^{18}\text{O}$ value. Ref: starting reference level for the calculated temperature variations.

Age	Biozone	Samples from contiguous layers	Value of $\delta^{18}\text{O}$ (SMOW)	Temperature profit and loss calculations	Samples from single layers	Value of $\delta^{18}\text{O}$ (SMOW)	Temperature profit and loss calculations	
Aquitanian	MN2	H	21.6	-				
		G	21.7	+2°				
Oligocene/ Miocene boundary	MP30/MN1	F	22	+1°	f	22.3	-3°	
Chattian	MP30	E	22.2	-2°	e	22	+1°	
		D	21.8	-	d	22.7	+3°	
		C	21.8	+1°				
		B	21.7	-4°	c	22.5	-3°	
		A	21.2	Ref	b	21.8	+2°	
					a	22.4	Ref	

weighing less than 500 g, which is the case for most of the Oligocene rodents. In this case, the change between the Late Oligocene and earliest Miocene faunas could be related to one or more successive climatic changes associated to enhanced seasonality (Huguency, 1984; Comte, 2000; Becker *et al.*, 2002).

The most comprehensive studies of the Chattian/Aquitanian floras and microfloras and their relationships to paleoclimates were mostly carried out on the western border of the Mediterranean Sea (Rhône Valley, Provence, Languedoc Roussillon, Catalonia, Portugal). The occurrence of some species (*Prosopis*) in the Provence area, the Swiss Molasse (Berger, 1990) and the Northern German Tertiary (Utescher, 2000) may indicate increasing climatic aridity during the Late Oligocene and Early Miocene (Guinet, 1984). Regression of angiosperms and the correlative development of Pinaceae and herbaceous plants reflect a dry period before the return of the Aquitanian-Burdigalian thermophilic floras (Chateaufneuf, 1972; Chateaufneuf and Nury, 1995; Bessedik, 1985; Pais, 1986).

The results obtained from the present study enable to outline the modality of the climatic evolution through the Oligocene/Miocene boundary in the Limagne graben. The sedimentary analysis of the late Oligocene deposits records an increase in palustrine indicators (mudcracks, root traces), reflecting a retreat of the shoreline. The lake water changed

from fresh to brackish during the Chattian (Huguency *et al.*, 2003) as testified by the presence of specific gastropods (*Hydrobia sp.*) and flamingo nests (*Paleolodus ambiguus*). This period is also characterized by the development of thanatocenoses of tenches preserved in the argillaceous beds of the end of the Oligocene.

Throughout the Oligo-Miocene boundary, the lacustrine faunal associations show a general evolution from brackish to fresh water (Tab. 7), as indicated by the appearance of freshwater ostracods and gastropods, a major development of caddisflies, and the disappearance of brackish-water gastropods (Huguency *et al.*, 1999; Huguency *et al.*, 2003).

Furthermore, the stable isotope compositions of stromatolites indicate that evaporation increased gradually toward the Oligocene/Miocene boundary.

The pollen data confirm this trend of increasing aridity furthermore revealing a cooling stage at the Oligocene/Miocene transition. These cool conditions were first highlighted by Gorin (1975), based on the presence of Pinaceae-rich pollen assemblages. The increasing aridity associated with a cooler climate may have led to the well-documented mammal impoverishment (Huguency, 1984; Legendre, 1987, 1989; Comte, 2000; Becker *et al.*, 2002)

A wetter climate prevailed during the lower part of the Aquitanian (MN1) followed by a gradual increase in temperature toward the upper part of the Aquitanian (MN2).

Table 7. Summary of climatic and environmental variations around the Oligocene/Miocene boundary determined from the sedimentology and lacustrine faunal and vegetal associations in the Limagne basin.

Age	Bio zone	Facies	Faunal data	Floral data	Environments	Climatic trend
Aquitanian	MN2a	Alternation of marl and calcarenite with root traces	Caddisflies Cyprinidae (tenches) Beaver <i>Valvata</i> sp. <i>Pseudamnicola</i> sp.	Pinaceae Graminaceae Cyperaceae Cupressaceae	Lacustrine environment –shallow fresh water	Dry and cold
	MN2a		Miliolidae Caddisflies	Palm tree Characeae		
	MN1	Alternation of marl, calcarenite with channels of detrital sand	Caddisflies	Cyperaceae	Lacustrine environment –shallow fresh water and fluvial arrivals	Wet and warm
			Cyprinidae (tenches) <i>Valvata</i> sp. <i>Pseudamnicola</i> sp.	Cupressaceae Euhorbiaceae Juglandaceae		
MP30/MN1		Alternations of marl, calcarenite with root traces and mudcracks, lacustrine limestone	Flamingos <i>Hydrobia</i> sp. Cyprinidae (tenches)	Discrepancies of Chattian floras	Shoreline retreat <i>Tenches thanatocoenosis</i> Brackish water	Aridity event
Chattian	MP30	Alternation of marl, calcarenite with root traces and ostracod-rich calcarenites	Beaver Cyprinidae (tenches) Caddisflies <i>Pseudamnicola</i> sp. (rare)	Gramineae Cyperaceae	Lacustrine environment –shallow fresh water	Dry and cold
	VI		Ostracods dominant Cyprinidae (tenches)	Cupressaceae Chenopodiaceae		
	MP29 V	Alternation of marl and calcarenite, ostracod-rich calcarenite, channels of detrital sandstone locally	Caddisflies <i>Pseudamnicola</i> sp. (rare) Ostracods dominant	Ericaceae Ulmaceae Juglandaceae Fagaceae Oleaceae Pinaceae Cupressaceae Cyperaceae	Lacustrine environment –shallow fresh water	Wet and warm

A cooler climate prevailing during the lower part of the Aquitanian is supported by the presence of Pinaceae-rich pollen assemblages (Gorin, 1975) and by the high fish tooth $\delta^{18}\text{O}$ values measured throughout the Chattian/Aquitanian boundary.

Our study confirms that the global climate evolution around the Oligocene/Miocene boundary involved several successive temperature changes as already suggested by Huguency (1984), Comte (2000) and Becker *et al.* (2002), along with a general trend of increasing aridity that settled during the Aquitanian (Tab. 7).

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