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GROUPE FRANÇAIS d'ETUDE du JURASSIQUE

Field Trip GUIDE BOOK

Integrated stratigraphy of some key Callovian-Oxfordian boundary sections in South-East France. Contribution to the choice of the Global Boundary Stratotype Section and Point (GSSP) of the Oxfordian Stage

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Field guide 2013

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Oxfordian GSSP Workshop
30th September-2nd October 2013

Integrated stratigraphy of some key Callovian-Oxfordian boundary sections in South-East France.
Contribution to the choice of the Global Boundary Stratotype Section and Point (GSSP) of the Oxfordian Stage.

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Cover photograph: Callovian-Oxfordian boundary at Thuoux (Subalpine Basin)

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Brief Schedule

Monday 30th September

11:00 a.m-2:00 p.m. Valence Gare TGV pick-up point (leaving Valence at noon)

Picnic lunch at the "Saut de la Drôme" near Luc-en-Diois

3:00 p.m.-6:00 p.m. Visit of the Saint-Pierre d'Argençon section

8:00 p.m. Dinner at the Hotel le Céans, Les Bègües-Orpierre.

Tuesday 1st October

7:30 a.m. Breakfast at the Hotel le Céans

8:30 a.m.-2 p.m. Visit of the Thuoux section and complementary section at Les Richers

Picnic lunch (buy a picnic after breakfast)

2:30 p.m.-6:00 p.m. Visit of the Lazer section

6:30 p.m. Discussions, including D. Fortwengler's ammonite collection

8:00 p.m. Dinner at Hotel le Céans, Les Bègües-Orpierre.

Discussions will continue after dinner

Wednesday 2nd October

7:30 a.m. Breakfast

8:30 a.m.-11:30 a.m. Visit of the Savournon section

11:30-12:15 Picnic lunch (buy a picnic after breakfast)

12:15 Departure for Valence Gare TGV (arrival around 3:00 p.m.)

Introduction

In Western European basins, the Callovian-Oxfordian transition is frequently marked by hiatuses or condensed levels. The scarcity of available ammonite-rich continuous sedimentary series, allowing precise ammonite biostratigraphy and integrating ammonite taxa from various palaeobiogeographic provinces, renders difficult the choice of a reliable section to define a Global boundary Stratotype Section and Point (GSSP) for the Middle-Late Jurassic transition. In this context, the Savournon section (Subalpine Basin, SE France) and the Redcliff Point/Ham Cliff section (Weymouth, UK) were proposed as potential candidates for the Callovian-Oxfordian GSSP. Previous meetings were organised in the Subalpine Basin in 1993, by the Groupe Français d'Étude du Jurassique (GFEJ), and by the Oxfordian Working Group (OWG) – International Subcommission on Jurassic Stratigraphy (ISJS) in 1994 (Atrops *et al.*, 1993; Atrops & Meléndez, 1994) but, since then, no official decision about this GSSP has been ratified.

Twenty years later, in view of new advances in the stratigraphy of the Terres Noires Formation, the objective of this field workshop is to revisit Savournon and Thuoux, together with two new sections in the Subalpine Basin (Saint-Pierre d'Argençon and Lazer), as potential candidates for the Callovian-Oxfordian GSSP. The Middle-Late Jurassic transition, including tectonic, sedimentological, geochemical and biostratigraphic aspects, has been studied, over several decades, in numerous well-exposed outcrops in the Diois, the Baronnies and the Buëch valley (e.g. Artru, 1972; Tribovillard, 1989; Dardeau et al., 1994; de Graciansky et al., 1999; Fortwengler & Marchand, 1994a-b-c-d; Fortwengler et al., 1997; Pellenard, 2003; Pellenard & Deconinck, 2006; Courtinat, 2006; Boulila et al., 2008; Giraud et al., 2009; Boulila et al 2010; Fortwengler et al., 2012; Pellenard et al., 2013a). In many sections of this domain, numerous well-preserved ammonites provide an accurate biostratigraphy for the Middle-Late Jurassic transition. Four outcrops where the Callovian-Oxfordian boundary is particularly well exposed were selected for the three days of the workshop: the Thuoux, Saint-Pierre d'Argençon, Lazer and Savournon sections, which allow all ammonite biohorizons and subzones of the uppermost Callovian Lamberti Zone and basal Oxfordian Mariae Zone to be clearly identified.

Geographic setting of the field trip

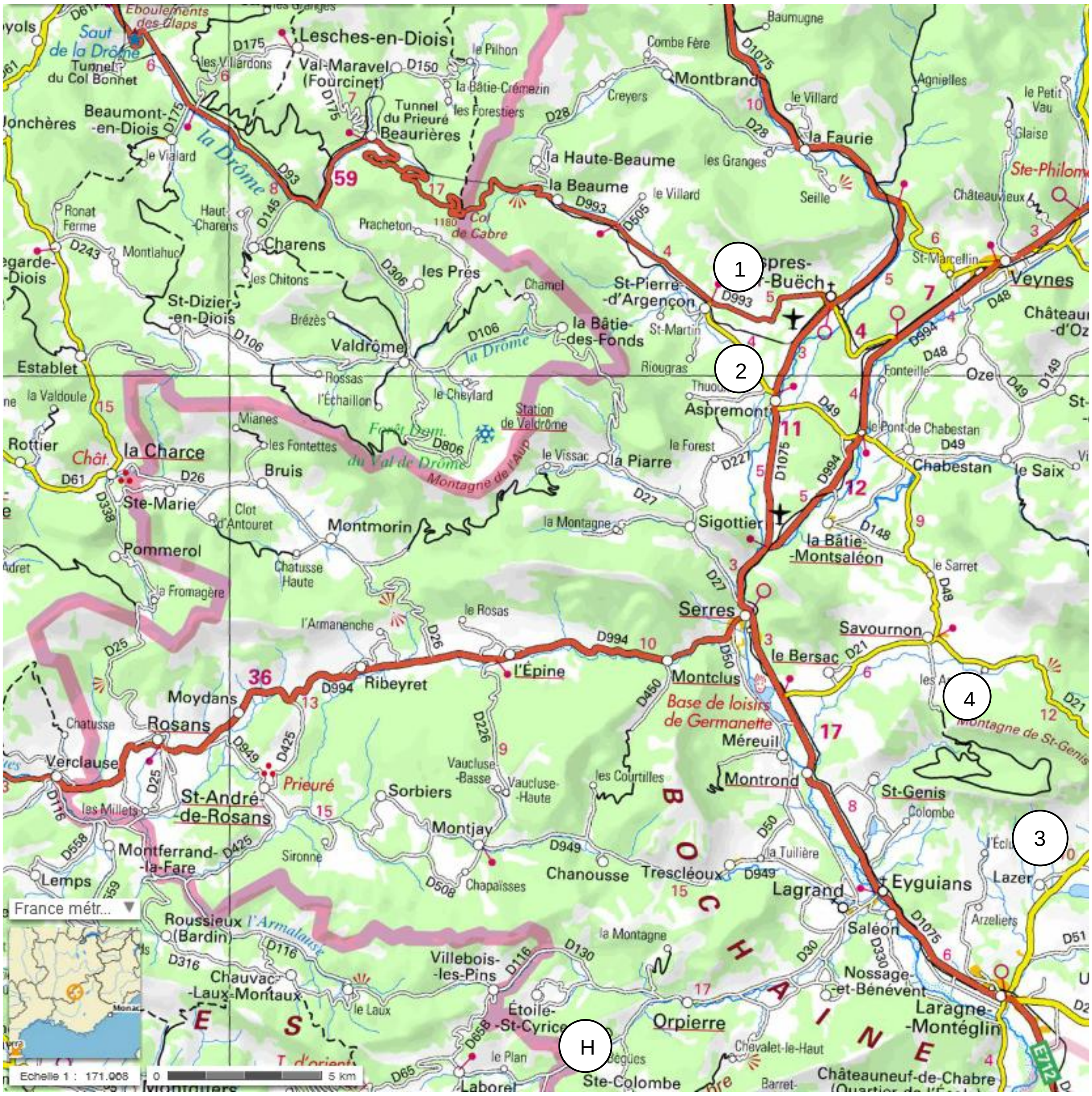


Figure 1: The sections visited during the field trip (1: Saint-Pierre d'Argençon; 2: Thuoux; 3: Lazer; 4: Savournon) and Hotel le Céans (H) in Les Bègües-Orpierre.

Geological setting of the field trip

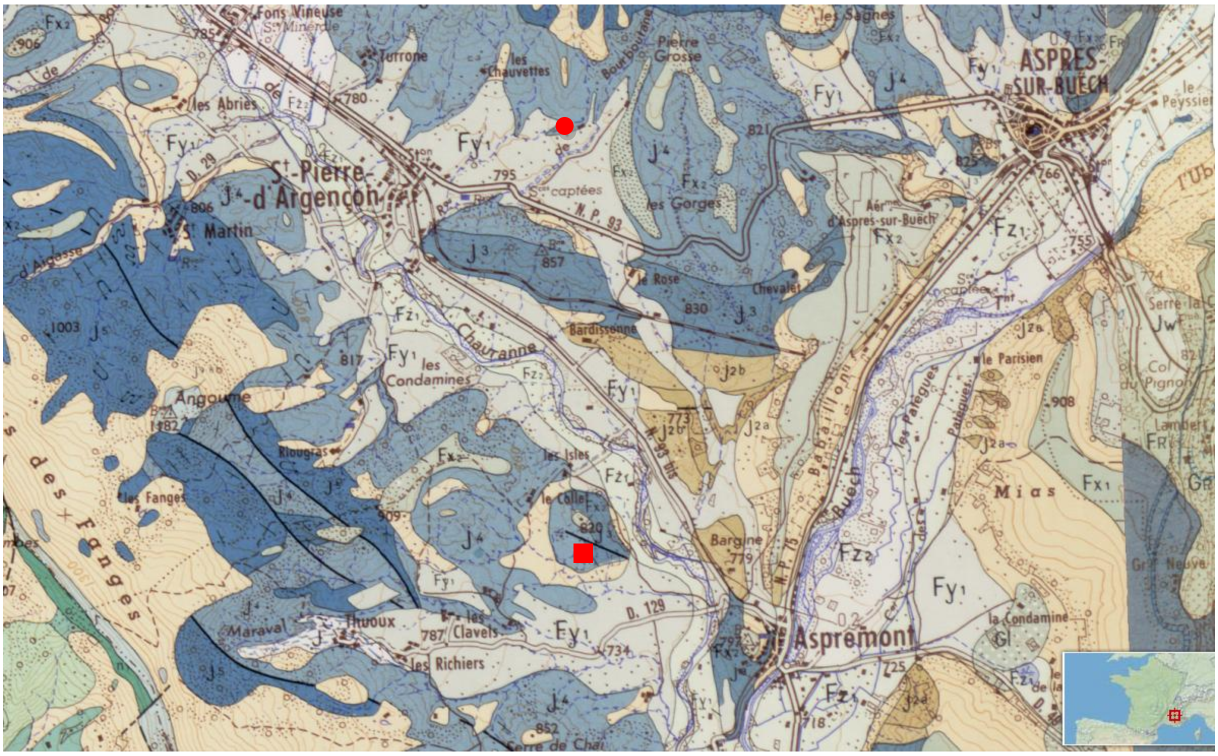


Figure 2: Geological map of the north part of the field trip: Saint-Pierre d'Argençon (circle) and Thuoux (square)

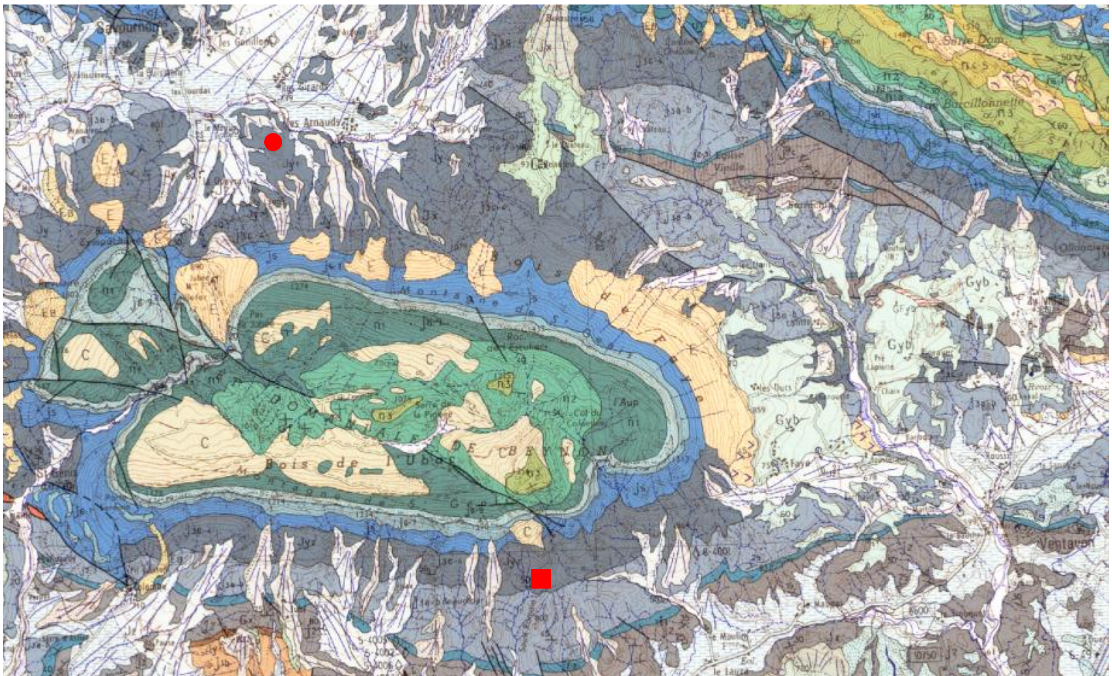


Figure 3: Geological map of the south part of the field trip: Savournon (circle) and Lazer (square)

The Subalpine Basin and the Terres Noires Fm

The palaeogeographic setting of the Subalpine Basin

During the Jurassic, the Subalpine Basin (South-East France) formed part of the External Alpine Realm or Dauphinois Realm (Baudrimont & Dubois, 1977; Dubois & Delfaud, 1989). Four geographically and tectonically defined areas can be recognised within this basin (Fig. 4):

- On the south-western margin, the Vivaro-Cevenol Platform (to the south of the French Massif Central), is the maximum western extent of the Subalpine Basin.

- On the south-eastern margin, the Provençal Platform includes the Digne and Castellane arcs.

- To the north, the Subalpine Range includes the Chartreuse and Vercors ranges.

- The central part of the Subalpine Basin includes the Diois, Baronnies and Dévoluy areas, where the Terres Noires Formation deposits are extensive and visible in thick outcrops.

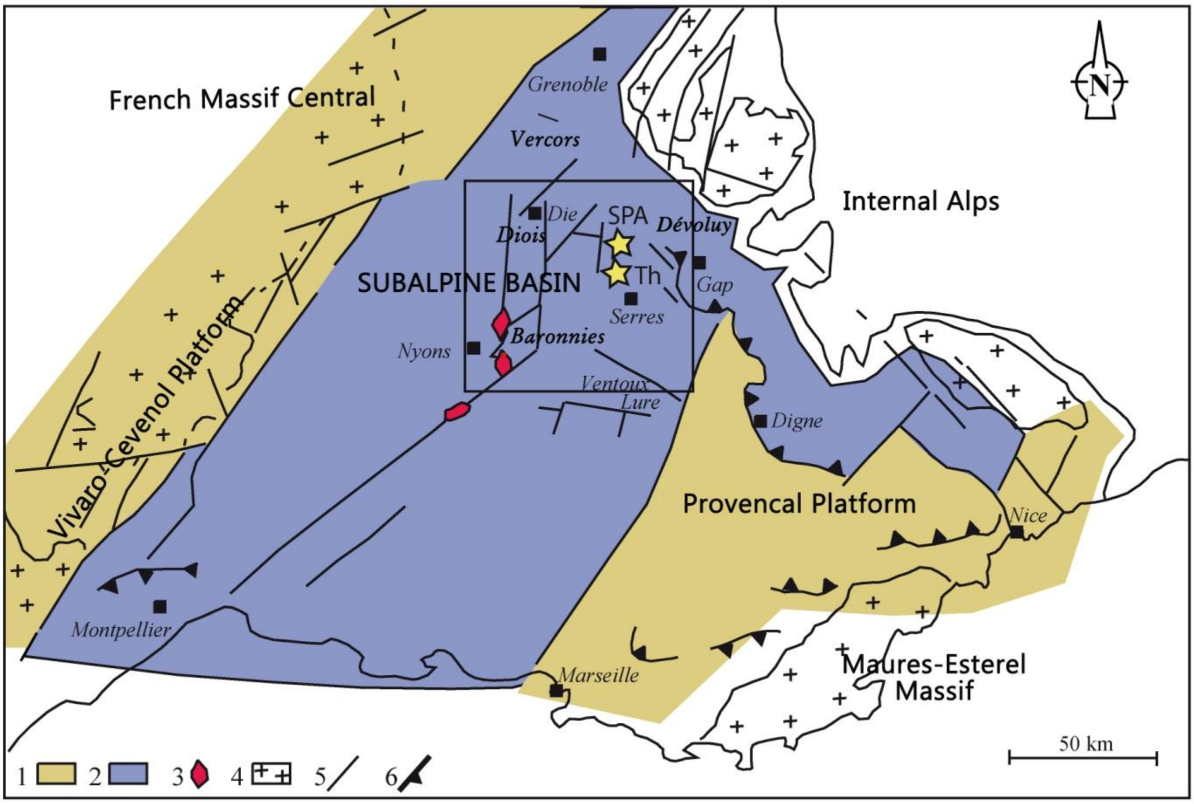


Figure 4: The Subalpine Basin in SE France (1: margins of the basin; 2: centre of the Subalpine Basin; 3: diapirs; 4: crystalline basement; 5: major faults; 6: thrust sheets)

During the Middle Callovian-early Middle Oxfordian interval, a thick layer of fine detrital sediment accumulated in the Subalpine Basin, forming thick shales and marls, with some indurated argillaceous limestone beds. This Terres Noires Fm can reach 2000 m thick in the Diois and Baronnies areas, the maximum subsidence zone of the basin (Artru, 1972). On the basin margins, the Terres Noires Fm is only a few hundred or tens of metres thick, and may be absent from ridges and shoals (Fig. 5).

During the Bajocian-Oxfordian interval, the Subalpine Basin was extremely subsident, opening eastwards on to the Tethys Ocean through the Ligurian Trough (Enay *et al*., 1980; Thierry & Cariou, 1980; Thierry *et al.*, 2000). It was bordered by carbonate platforms throughout the Callovian and Oxfordian (Elmi *et al*., 1984; Enay *et al*., 1984; Atrops, 1994; de Graciansky *et al*., 1999).

The structural and geodynamic setting

During the opening of the Tethys Ocean, the reactivation of Hercynian faults partially controlled sediment distribution. This extensional tectonics, driven by distensive faults, was the final episode of Tethyan rifting. At the same time, generalised subsidence coincided with the first opening of the Atlantic Ocean. Jurassic transform faults and synrift extension affected the subsequent geometry and palaeomorphology of the north-west borders of the Subalpine Basin (Lemoine, 1984; de Graciansky & Lemoine, 1980; Lemoine *et al.*, 1986, 1989; Lemoine & de Graciansky, 1988). The main tectonic phases in the Subalpine Basin occurred from the Lower-Middle Bathonian boundary (Progracilis/Subcontractus/Morrisi Zones) to the Middle Oxfordian (Plicatilis/Transversarium Zones).

Several studies have provided evidence of a structural control on clay sedimentation for the Terres Noires Fm, attested by the presence of tilted blocks throughout the basin (Fig. 6; Artru, 1967; Dardeau et al., 1994; Pellenard 2003). Some major faults of Hercynian origin were reactivated during the rifting phase, causing synsedimentary diapirism in the central part of the basin, which also contributed to block tilting and local thickness variations in the Terres Noires Fm (Dardeau *et al*., 1990).

On the margins of the basin, the block-tilting dynamics was well marked until the Upper Bathonian. A major unconformity is recognised at the Dogger-Malm transition, generating stratigraphic gaps for the Upper Callovian-Lower Oxfordian interval on the Vivaro-Cevenol Platform (Elmi, 1990), on the Provençal Platform (Bourseau & Elmi, 1980; Floquet *et al*., 2007), and on the Subalpine Range (Dardeau *et al*., 1988; Atrops *et al*., 1989).

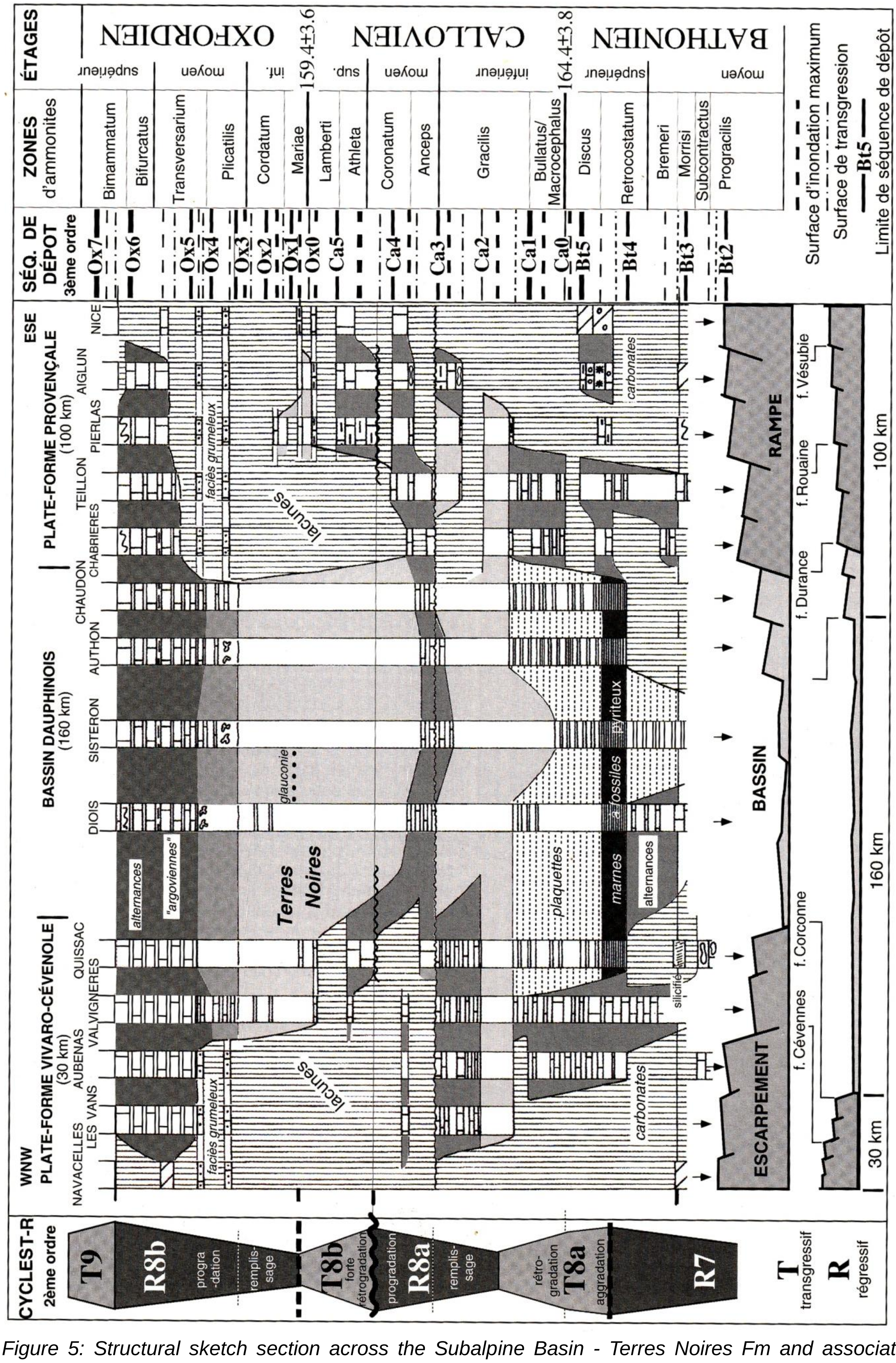


Figure 5: Structural sketch section across the Subalpine Basin - Terres Noires Fm and associated chronostratigraphic diagram (de Graciansky et al., 1999).

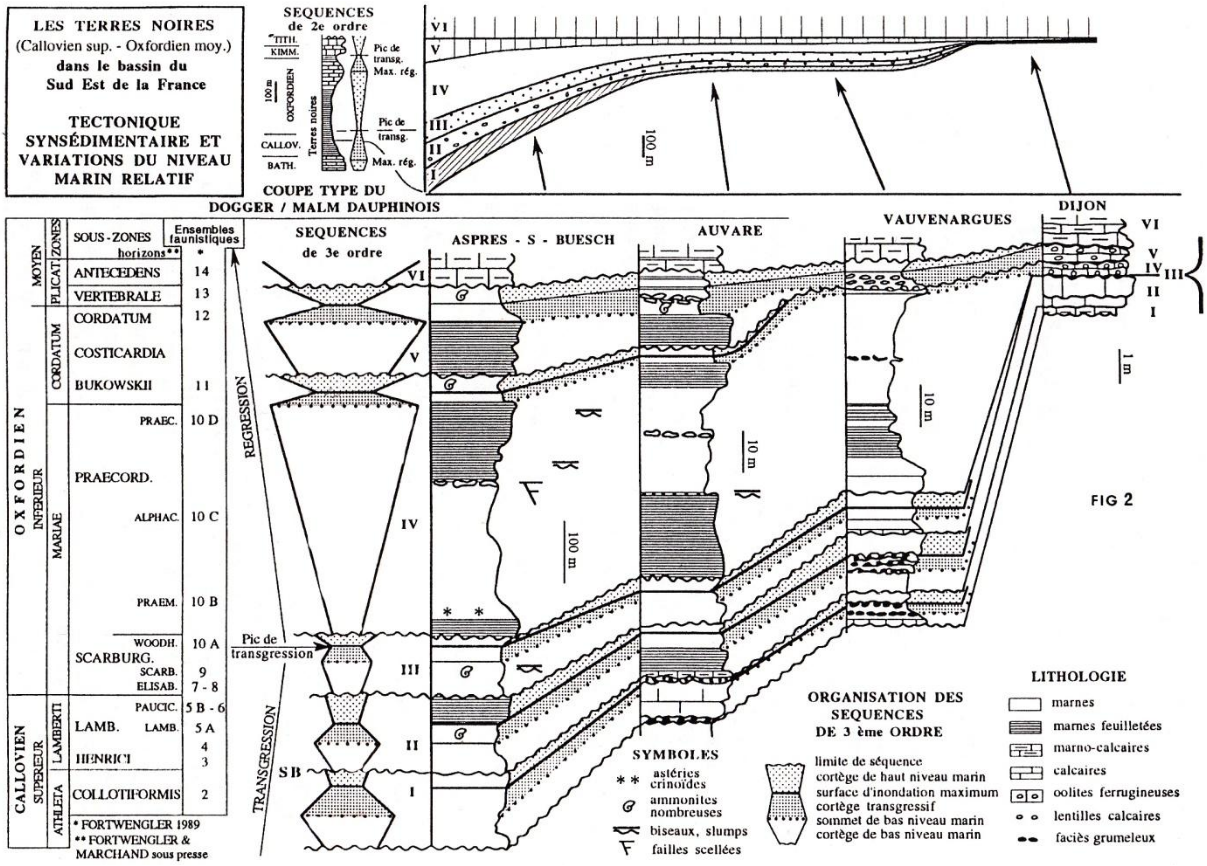


Figure 6: Depositional sequences sensu Vail in the Terres Noires Fm. Depositional sequences II to IV display thickness variations between the basinal sections (e.g. Aspres-sur-Buëch/Saint-Pierre d'Argençon) and the platform margin sections (e.g. Vauvenargues, Auvare), implying extensional synsedimentary faulting during the Callovian-Oxfordian interval (Dardeau et al., 1994).

The Terres Noires Formation

From the Late Bajocian (Parkinsoni Zone) to the Middle Oxfordian (top of the Antecedens Subzone, Plicatilis Zone), fine detrital sediments were continuously deposited in a very subsident basin, implying a high sedimentation rate (Artru, 1972; Fortwengler, 1989; Tribovillard 1989; Pellenard 2003). These deposits are known as the Terres Noires Fm, which is up to 2000 m thick in the central part of the Subalpine Basin (Figs. 7, 8).

The Upper Bajocian-Bathonian interval, described as the lower member of the Terres Noires Fm ("membre inférieur" *in* Artru, 1972), is characterised by dolomitic dark marls with some platy limestone intercalations. From the Lower Callovian to the Middle Oxfordian, in the centre of the Subalpine Basin, thick sedimentation was dominated by clayey and silty calcareous deposits (upper member, "membre supérieur" *sensu* Artru). In many areas, (e.g. Laragne), the Callovian is up to 400 m thick and the base of the stage is marked by a bundle of clayey limestone beds, well dated by ammonites (Bullatus-Macrocephalus Zone). This unit is the median marker-bed ("niveau repère médian") described by Artru (1972, Fig.7).

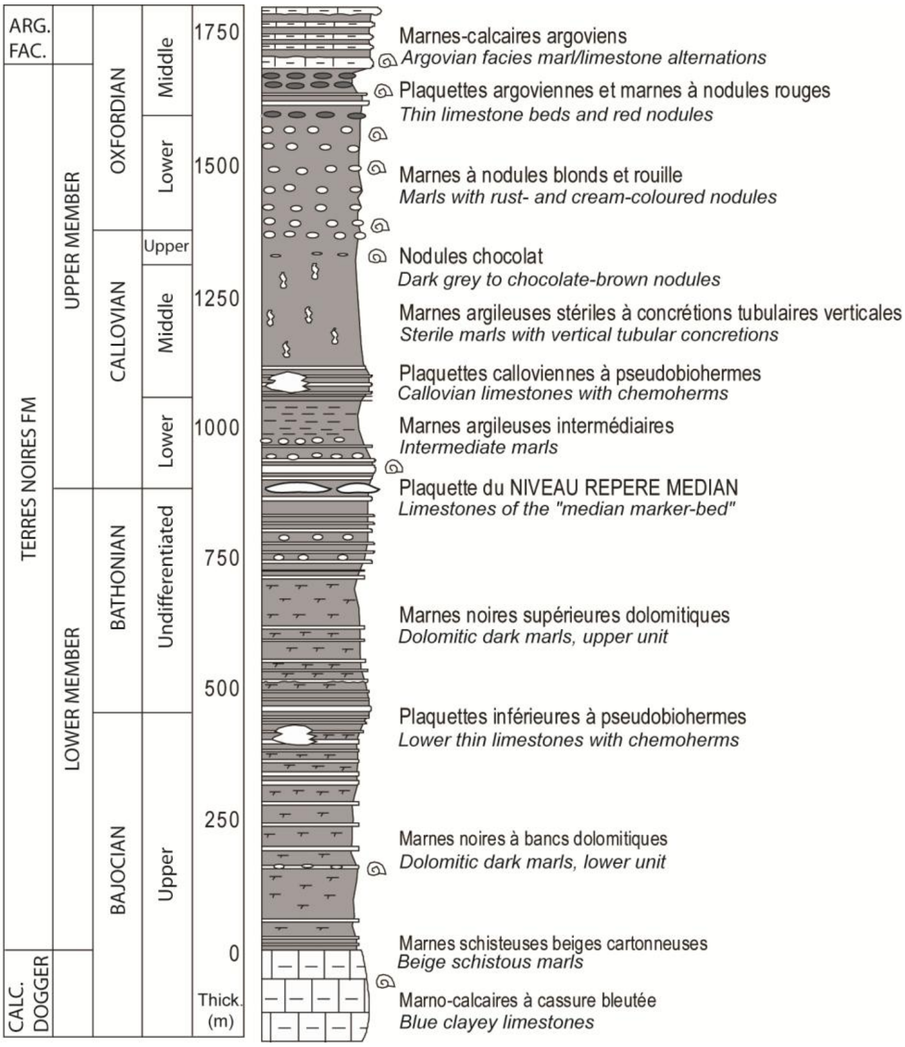


Figure 7: Synthetic log of the Terres Noires Fm (after Artru, 1972 in Pellenard, 2003)

In the eastern part of the Subalpine Basin (Buëch and Durance valleys), several types of calcareous nodules can be observed:

- At the base of the Upper Callovian, quite large, dark grey nodules sometimes form groups, known as “cauliflower” concretions.

- In the Upper Callovian and at the base of the Lower Oxfordian, small, dark grey to chocolate-brown nodules are aligned in beds.

- Above, the marls contain beds of aligned cream-coloured nodules and larger, flatter, rust-coloured nodules containing fine laminations interpreted as distal tempestites (Pellenard, 2003).

- The top of the Terres Noires Fm shows beds of aligned red nodules, especially north-east of Laragne. Marl deposits become more and more calcareous until true marl/limestone alternations appear, also known as the Argovian facies.

In both the Callovian and Oxfordian deposits, large mineralised columnar or lenticular calcareous concretions are sometimes found. They are interpreted as chemoherms associated with seep deposits, resulting from synsedimentary hydrothermalism (Gaillard et al., 1985; 1992; 2011). These chemoherms contain abundant specific benthic fauna, such as the atypical irregular echinoid species, *Tithonia oxfordiana*, in association with gastropods, bivalves and sponges (Gaillard et al., 2011). One of the best examples of this chemoherm with its associated ecosystem was found at Beauvoisin (Drôme). Smaller mineralised concretions (*e.g*. calcite, pyrite) of the same type are frequently observed throughout the Terres Noires marls.

Marls of the Terres Noires Fm are composed on average of 30% carbonates and of a mixture of silt (mainly detrital quartz) and clay fractions (Pellenard 2003). Clay assemblages are relatively homogeneous and are composed of iron-rich chlorite (15-20%), illite (35-50%), R1 illite-smectite mixed-layer minerals (25-50%), and kaolinite (10%). Few variations are identified between the centre of the basin and the Vivaro-Cevenol Platform, while the eastern part of the basin, more affected by burial diagenesis and alpine metamorphism, presents illite and chlorite values that increase eastward (Barlier *et al.*, 1974). The west margin of the Subalpine Basin is the only area to record a mineralogical change, with significantly increased proportions of smectites during the Upper Callovian (Pellenard & Deconinck 2006). Interbedded with the Terres Noires marls, several thin bentonite deposits (weathered volcanic ash layers) have been identified, thus allowing correlations between the Subalpine Basin and the Paris Basin (Pellenard *et al.*, 2003; Pellenard & Deconinck 2006, Fig. 8).

Marl and bentonite mineralogy clearly reveals the overprint of burial diagenesis on the sediment. Nevertheless the nature of the illite-smectite mixed-layer clay minerals and the organic matter Tmax (450°C on average) suggest moderate burial diagenesis in the centre and western part of the basin, probably never exceeding 120-150°C during maximal burial, which occurred during the Lower Cretaceous (Guilhaumou *et al*., 1996).

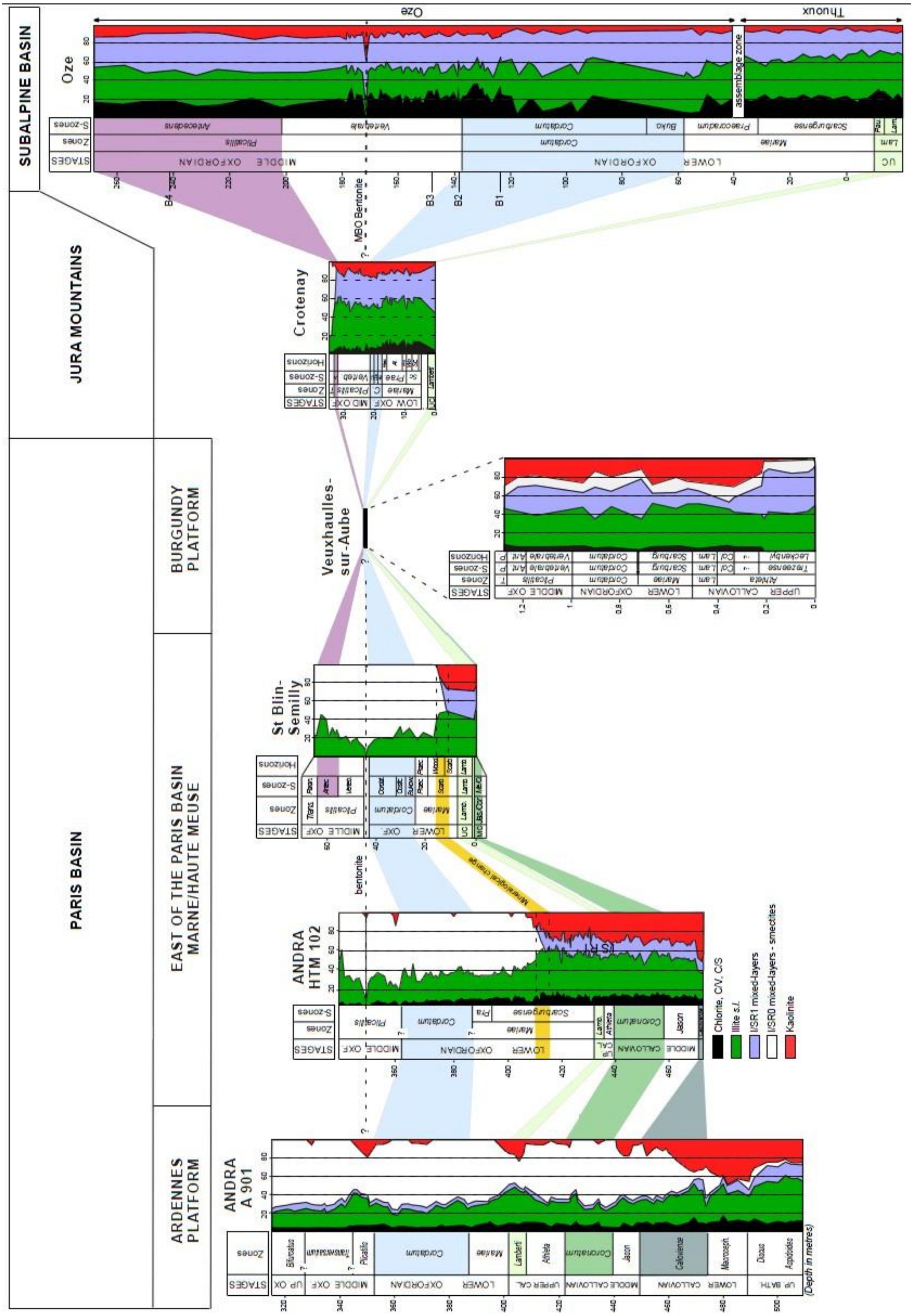


Figure 8: Clay mineralogy and correlations of the Callovian-Oxfordian in the Paris Basin (boreholes), the Jura Mountains and the Subalpine Basin outcrops. A bentonite layer is taken as an isochrone for correlations betweens the Paris Basin and the Subalpine Basin (Pellenard & Deconinck 2006).

Biostratigraphy in the Subalpine Basin and choice of sections

The Subalpine Basin is part of the Submediterranean palaeobiogeographic realm. The Terres Noires Fm is therefore calibrated following the ammonite zonal scheme established for this faunal province (Thierry *et al.*, 1997; Cariou *et al.*, 1997). However, the ammonite associations are rich in Cardioceratinae, characteristic of the Subboreal Realm (Marchand *et al.*, 1990). It is therefore necessary to use both zonal schemes, thus enhancing the correlations between the two faunal realms, providing maximum precision for the relative age determination of the sedimentary units.

Although well-preserved ammonites are abundant in the Terres Noires Fm, where they greatly exceed other fossil macroinvertebrates (*e.g.* belemnites and brachiopods), several microfossil groups provide additional, indispensable biostratigraphic data (calcareous nannofossils, dinoflagellates, spores and pollen, foraminifera and ostracods).

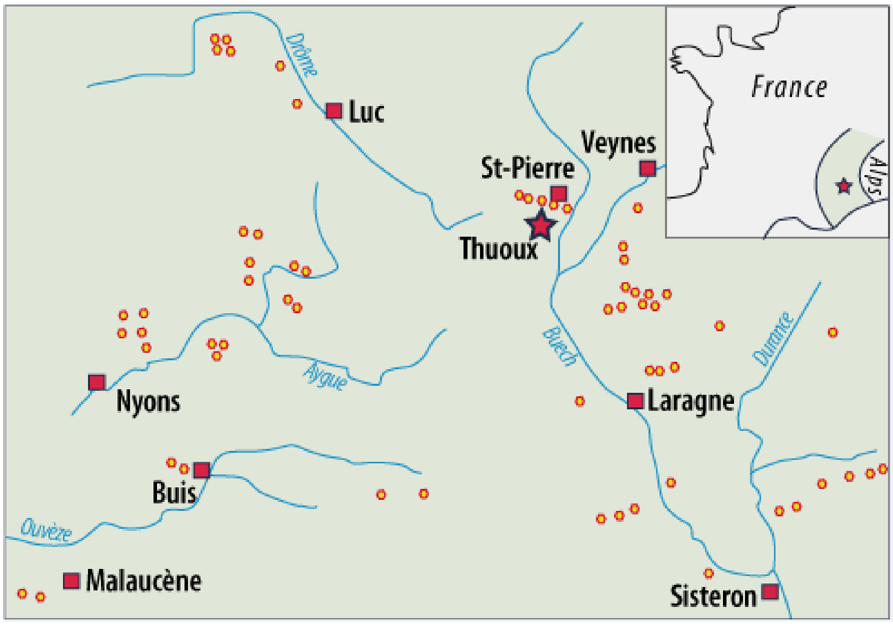


Figure 9: Map of the 61 outcrops (red circles) where the Callovian-Oxfordian boundary has been recognised, including the Thuoux section (red star).

The reference sections for the Subalpine Basin

There are many easily accessible outcrops in the Subalpine Basin where the Terres Noires Fm is present (Fig. 9), but only a few are suitable for high-resolution biostratigraphic investigations (Fig. 10). The sections selected are in the River Buëch valley, between Aspres-sur-Buëch and Sisteron. Here the Terres Noires Fm is very rich in well-preserved ammonites, and particularly extensive, with no disconformities, faults, or hiatuses. Two sections, Thuoux and Savournon, have been investigated in detail and previously published: Thuoux is proposed as the type section, as the candidate for the Callovian-Oxfordian GSSP, while Savournon could be an auxiliary section (Fortwengler, 1989; Fortwengler & Marchand, 1994c-d; Fortwengler *et al*., 1997, 2012). A third section, Saint-Pierre d'Argençon, where the same lithological and faunal successions have been observed, was more recently described, confirming results obtained at the Thuoux and Savournon outcrops. It could also be an auxiliary section. It was recently used for a precise orbital calibration of the Oxfordian, from the magnetic susceptibility signal (Boulila *et al.*, 2008, 2010).

In the sections in the eastern Diois and in the Baronnies, the *lamberti* and *paucicostatum* biohorizons flanking the Callovian-Oxfordian boundary are either not well preserved, or contain few characteristic fossils. The sections in the east (Gap/Embrun) have a poor fossil record, with some hiatuses. In this area, the Terres Noires Fm deposits, like other Jurassic sediments, were strongly affected by alpine metamorphism (Artru, 1972). The sections near the margins of the basin (La Voulte-sur-Rhône, on the Vivaro-Cevenol Platform, and Vauvenargues on the Provencal Platform) can be used to provide supplementary material, despite frequent hiatuses during the Callovian-Oxfordian interval.

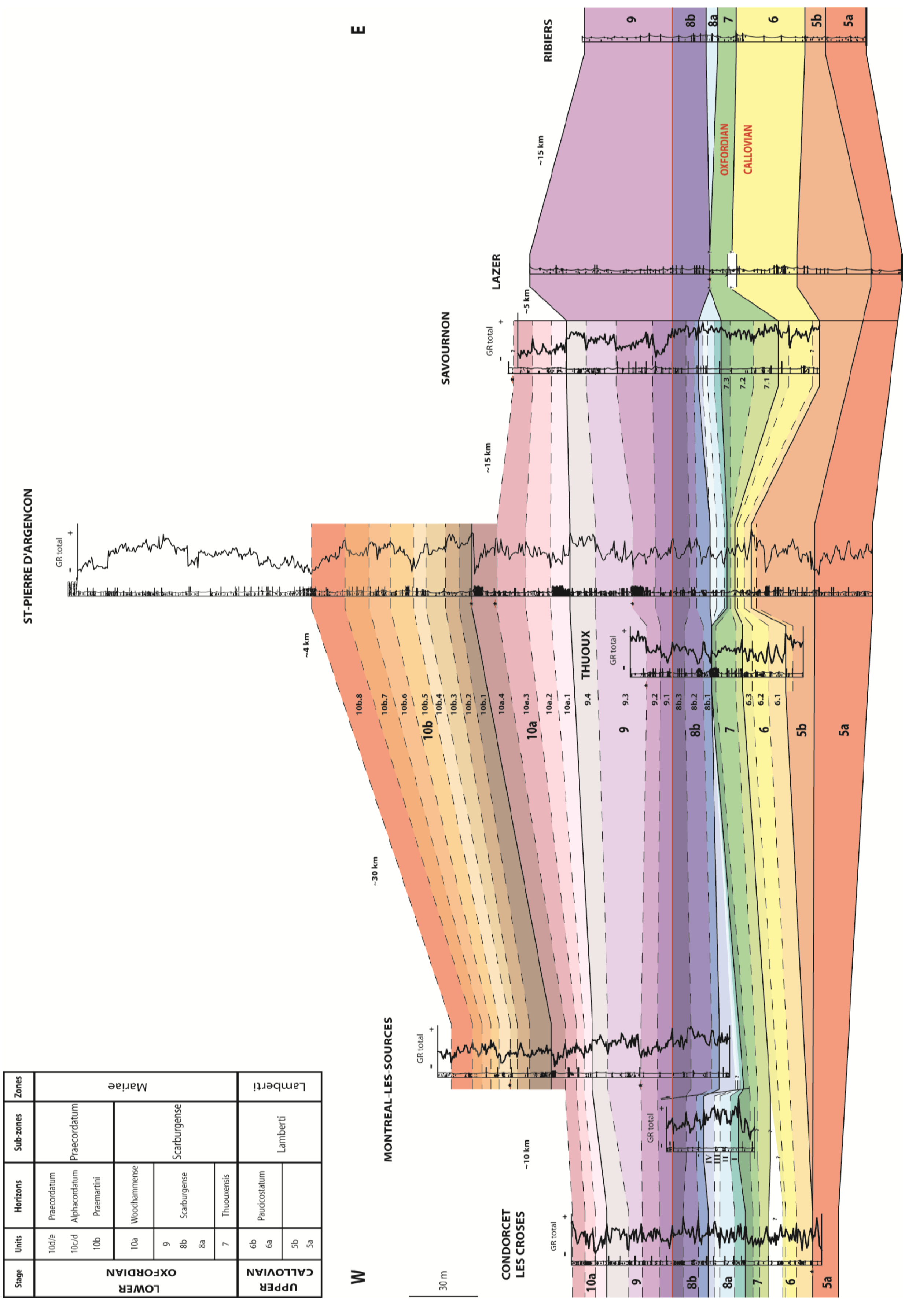


Figure 10: Correlation of selected sections using ammonite zonal scheme and field gamma-ray data (Gaspard, 2005; Pellenard et al., in progress).

Ammonite zonal scheme, biostratigraphy and chronostratigraphy

Bajocian-Upper Callovian

Around Serres/Laragne and the Durance valley, for the first 200 m of marly sediments at the base of the Terres Noires Fm, an Upper Bajocian (Parkinsoni Zone) age is proposed, using ammonite data (Gidon *et al*., 1991). The next 500 m of sediments present a poor fossil record, with few ammonites, nevertheless suggesting a Bathonian age (Artru, 1972). Locally, near Condorcet (Dardeau *et al*., 1988), the Upper Bathonian has been identified from salient ammonites of the Retrocostatum Zone and the Discus Zone. In the Laragne area, the "niveau repère médian" (median marker bed) encloses calcareous nodules, with a lowermost Callovian ammonite fauna of the Bullatus (Macrocephalus) Zone. The next 380 m of marly sediments have no characteristic fossils (Artru, 1972); they could be Lower and Middle Callovian, as they are bracketed by the lowermost Callovian median marker bed and the first layers dated as the Athleta Zone (Upper Callovian). Many pyritous ammonites of the Middle Callovian Jason Zone and Coronatum Zone have been found in this marly interval in the Baronnies, near Condorcet (Dardeau *et al*., 1988).

Upper Callovian

In the Terres Noires Fm, the presence of characteristic ammonite species records the majority of the zones, subzones and biohorizons defined for the Submediterranean Realm (Fig. 11).

* **Athleta Zone** (d'Orbigny, 1852; Oppel, 1857, *sensu* Callomon 1962, published 1964)

This zone can be identified throughout the basin; it has a medium thickness of about 50 m. The index species, *Peltoceras athleta* Philips, can often be found in association with numerous Phylloceratinae.

° **Trezeense Subzone** (Cariou, 1969; Level 1 *in* Fortwengler, 1989).

The presence of *Pseudopeltoceras* underlines the beginning of the Upper Callovian. The associated fauna including Peltoceratinae (*Peltoceras baylei* Prieser macroconch, *Rursiceras pseudotorosum* Prieser microconch), Hecticoceratinae, Oppeliidae, Perisphinctidae and Phylloceratinae, is characteristic of the upper part of the subzone.

° **Collotiformis Subzone ?** (Bourquin & Contini, 1968; Level 2 *in* Fortwengler, 1989).

The Collotiformis Subzone is not always easily identified. Peltoceratinae disappear while conversely Kosmoceratidae appear. *Collotia cf. odyssea* (Mayer) can be used as a good argument for the presence of the subzone. Grossouvreinae (gr. *Grossouvria evexa-sulcifera* Quenstedt-Oppel) and Hecticoceratidae are still well represented, as are Phylloceratidae (mostly *Sowerbyceras tortisulcatum* d'Orbigny).

* L**amberti** Z**one** (Hébert, 1857, 1860, *emend*. Marchand, 1986; Levels 3, 4 and 5 *in* Fortwengler, 1989).

° **Henrici Subzone** (Sayn, 1830; Callomon & Sykes *in* Cope *et al*., 1980).

The index species *Quenstedtoceras henrici* (Douvillé), and *Distichoceras nodulosum* (Quenstedt) are present but rare, as are *Quenstedtoceras aff. messiaeni* Marchand & Reynaud (Level 3 *in* Fortwengler, 1989). The ammonite fauna is dominated by Hecticoceratinae (*Orbignyceras pseudopunctatum* Lahusen; *Brightia brighti* Pratt), Pseudoperisphinctinae (*Grossouvria evexa-sulcifera* Quenstedt-Oppel), Euaspidoceratinae and Phylloceratidae. In several sections (Buëch valley, Sahune district), a fossil-rich layer with *Peltoceras schroederi* Prieser can be used to define the top of the subzone.

° **Lamberti Subzone** (Callomon & Sykes *in* Cope *et al*., 1980).

Cardioceratinae species are used to define three successive biohorizons in the Lamberti Subzone.

- *praelamberti* Biohorizon (Marchand, 1986).

At the base (Level 4 *in* Fortwengler, 1989), Hecticoceratinae (*Putealiceras punctatum* Stahl) are frequent; they are accompanied by *Horioceras baugieri* (d'Orbigny) and *Alligaticera*s sp. Rare Cardioceratinae are present; some with morphotypes close to *Quenstedtoceras henrici* (Douvillé), while the majority can already be identified as *Quenstedtoceras praelamberti* (Douvillé).

Level 4 is easily recognised in the centre of the basin but is more difficult to observe elsewhere, especially on the margins.

Near the top, (Level 5A *in* Fortwengler, 1989) *Quenstedtoceras praelamberti* (Douvillé) is abundant, with characteristically fine, not very prominent ribbing, with only one or two intercalaries. Diverse accompanying fauna include *Orbignyceras paulowi* de Tsytovitch and *Kosmoceras duncani* (Sowerby). Level 5A is easily recognised throughout the basin and sometimes on the margins.

***- lamberti* Biohorizon** (Callomon, 1964; Level 5B *in* Fortwengler, 1989)

Cardioceratinae are very rare, and their ribbing morphology has changed: primaries have thickened, with more intercalaries.

Perisphinctinae and Pseudoperisphinctinae (*Alligaticeras* and *Poculisphinctes* genus) are frequent. Hecticoceratinae are represented mainly by *Hecticoceras pseudopunctatum* Lahusen. NO *Kosmoceras*, *Distichoceras* or *Berniceras* are found after the *lamberti* Biohorizon.

This biohorizon corresponds to a stratigraphic gap everywhere in the basin except for in the Buëch valley and the Propiac section (western part of the basin).

***- paucicostatum* Biohorizon** (Marchand, 1979, *emend*. Fortwengler & Marchand, 1991; Level 6 *in* Fortwengler, 1989; Fortwengler *et al.*, 1997)

The *paucicostatum* Biohorizon is the uppermost biostratigraphic unit of the Callovian. It can sometimes be divided into two parts if the unit is thick enough, with an abundant fossil record.

The lower part (Level 6A, *in* Fortwengler *et al.*, 1997) still contains some Cardioceratinae with a morphology very close to *Quenstedtoceras lamberti* (Sowerby).The morphologically more advanced individuals can be considered a distinct species: *Cardiocera*s *paucicostatum* Lange, with coarse, dense ribs, slightly more prorsiradiate, on an ogival venter without a keel (Lange, 1973; Debrand-Passard *et al*, 1978, Fortwengler & Marchand, 1994a; Fortwengler *et al.*, 1997). *Hecticoceras* (*Orbignyceras) paulowi* (de Tsytovich) is the most frequent of the Hecticoceratinae.

The upper part (Level 6B, *in* Fortwengler *et al.*, 1997) is characterised by relatively numerous *Peltoceratoides eugenii* (Raspail) which present duplicated latero-ventral tubercles for the first time since the base of the Upper Callovian (Bonnot, 1995; Bonnot *et al.*, 1997; Chapman 1999; Bonnot *et al.*, 2002). In Level 6B, a cardioceratid morphotype with a compressed shell section has been identified within the populations of *Cardioceras paucicostatum,* presenting clear morphological affinities with *Scarburgiceras scarburgense* (Young & Bird): ribs are denser and fine, almost never with intercalaries, and they end with a smooth and slightly raised siphonal band. *Hecticoceras* (*Orbignyceras) paulowi* (de Tsytovich) is less frequent than in Level 6A. No Pseudoperisphinctinae are found above Level 6B.

Level 6 (*paucicostatum* Biohorizon) can be identified wherever Level 5B (*lamberti*

Biohorizon) is present. The *paucicostatum* Biohorizon has been identified in the Buëch valley, near Sisteron and in several parts of the Baronnies. Elsewhere in the Subalpine Basin, its absence is associated to the *lamberti* Biohorizon gap.

Lower Oxfordian

There is a slight change in facies (from the end of the *paucicostatum* Biohorizon) to blue-grey marls, with frequent thin intercalations of calcareous beds and beds with aligned calcareous nodules. The total thickness of the Lower Oxfordian Substage varies from 300 to 400 m.

*** Mariae Zone** (Douvillé 1881; Levels 7-10 *in* Fortwengler, 1989; Fortwengler & Marchand, 1994a). The Mariae Zone is much thicker than the Cordatum Zone, which is frequently reduced and difficult to recognise.

° Scarburgense Subzone (Buckman, 1913)

New ammonite species of Cardioceratinae and Hecticoceratinae are used as index fossils to define three successive biohorizons in the Scarburgense Subzone.

- *thuouxensis* Biohorizon (Fortwengler *et al.*, 1997; Level 7 *in* Fortwengler, 1989; *elisabethae* Biohorizon, Fortwengler & Marchand, 1991, 1994a)

A marked faunal turnover took place in the *thuouxensis* Biohorizon. Many Callovian ammonite genera and subgenera disappeared (*Poculisphinctes, Orbignyceras, Putealiceras, Alligaticeras, Orionoides*), while new species appeared, in particular *Hecticoceras* (*Brightia) thuouxensis* Fortwengler & Marchand, which is easy to distinguish morphologically from the Callovian Hecticoceratinae (Fortwengler & Marchand, 1994a-b; Fortwengler *et al.*, 1997; Chapman, 1999). The Cardioceratinae are still morphologically close to those of the *paucicostatum* Biohorizon (Level 6B), although some show clear affinities with *Cardioceras scarburgense* (Young & Bird): the ribs on the body-chamber are decidedly prorsiradiate and the secondary ribs are almost never divided. The Peltoceratinae are very similar to those in the underlying level, but the latero-ventral tubercles are more clearly duplicated (Bonnot, 1995; Bonnot *et al.*, 1997, 2002). The Euaspidoceratinae reappear at the top of the biohorizon (Bonnot, 1995) with a new species, *Euaspidoceras armatum* (de Loriol), accompanied by the first *Properisphinctes bernensis* (de Loriol).

The *thuouxensis* Biohorizon has been identified throughout the Subalpine Basin and its margins. It can be considered as an outstanding marker-bed, as it is observed in more than 60 sections. It has also been formally identified in the Callovian-Oxfordian Argiles de la Woëvre Fm in the eastern Paris Basin (Thierry *et al.*, 2006), in the Jura Mountains (Jardat, 2010) and in the south of England (Chapman, 1999).

- *scarburgense* Biohorizon (Buckman, 1913, *emend*. Fortwengler & Marchand, 1994a; Levels 8 and 9 *in* Fortwengler, 1989; Fortwengler *et al.*, 1997).

Based on various ammonite associations, this biohorizon can be divided into three parts: 8A, 8B and 9 (Fortwengler & Marchand, 1994a-b, Fortwengler *et al.*, 1997, 2012).

Level 8A: *Hecticoceras (Brightia) thuouxensis* Fortwengler & Marchand is still present but discrete and gradually replaced by *Hecticoceras (Brightia) chatillonense* de Loriol (de Loriol, 1898; Fortwengler *et al.*, 1997). Macroconchs have weak ornamentation, while microconchs still have strong, but denser ribbing, as there are fewer intercalaries. Another species of Hecticoceratinae appeared, *Hecticoceras coelatum* (Coquand), collected for the first time in this level (Thierry *et al*, 2006), associated with *Taramelliceras episcopalis* de Loriol. Among the Cardioceratinae, many individuals have a narrower umbilicus, more sinuous ribbing and a more oval section. With a more marked prorsiradiate design, the ribs tend to form a chevron pattern on the venter; at the same time, the smooth siphonal band tends to disappear. All these morphological features are typical of *Cardioceras scarburgense* (Young & Bird). *Peltoceratoides eugenii* (Raspail) persists without morphological changes (Bonnot, 1995; Bonnot *et al.*, 1997).

Level 8B: The level begins with the first appearance datum of *Peltoceratoides athletoides* (Lahusen); the species shows a very clear duplication of the latero-ventral tubercles (Bonnot, 1995; Bonnot *et al.*, 1997; 2002) and rib-branching higher on the flanks than in *Peltoceratoides eugenii* (Raspail). Concerning the Oppellidae, *Hecticoceras* (*Brightia) thuouxensis* Fortwengler & Marchand are absent but *Hecticoceras* (*Brightia) chatillonense* de Loriol is still present. *Eochetoceras villersensis* (d'Orbigny) is more frequent but still rare (Douvillé, 1912; Chapman, 1997, 1999; Thierry *et al.*, 2006). The Cardioceratinae are the same as in Level 8A, but less frequent (only 4.6% of the total ammonite fauna), with an increasing number of variants with a thicker whorl section, and pronounced, wide-spaced ribs similar to *Cardioceras mariae* (d'Orbigny), prefiguring *Cardioceras* morphologies in the *woodhamense* Biohorizon. The Phylloceratina are very abundant here, with a high proportion of *Sowerbyceras tortisulcatum* (d'Orbigny).

Level 9: The upper part of the *scarburgense* Biohorizon (lower and middle part of Level 9) shows a drastic decrease in ammonite faunal diversity, coeval with a noticeable increase in Phylloceratina. In the most fossiliferous outcrops, we can observe the association of species generally linked to open sea or deeper environments (Thierry *et al*, 2006), such as *Eochetoceras villersensis* (d'Orbigny), *Lytoceras fimbriatum* (Sowerby) and *Lissoceras erato* (d'Orbigny).

At the top of Level 9, the genus *Properisphinctes* is more frequent, and Phylloceratina are still numerous. In rare outcrops in the Subalpine Basin, some Cardioceratinae with prorsiradiate ribs on the venter are morphologically close to *Cardioceras* w*oodhamense* Arkell, which possibly indicates the lowermost part of the *woodhamense* Biohorizon (Arkell, 1939; Fortwengler & Marchand, 1994a-b; Fortwengler *et al.*, 1997; Jardat, 2010). Like the *thuouxensis* Biohorizon, the *scarburgense* Biohorizon is recognised throughout the basin, but it is sometimes difficult to divide Level 8 into two parts, particularly on the margins.

- *woodhamense* Biohorizon (Fortwengler & Marchand, 1994a-b; uppermost part of Level 9 *in* Fortwengler, 1989; lowermost part of Level 10 *in* Fortwengler & Marchand, 1994a-b).

The Ammonitina are again frequent and more diversified. The Perisphinctinae form about one third of the total population, chiefly *Properisphinctes bernensis* (de Loriol). The Cardioceratinae are very rare, with the characteristic morphology found at the base of the *woodhamense* Biohorizon. Regarding the Oppeliidae, the genus *Brightia* is still present, with *Brightia matheyi* de Loriol, and the first *Campylites* are found.

° Praecordatum Subzone (Morley-Davies, 1916; Level 10 *in* Fortwengler & Marchand, 1994a-b)

At the base of the subzone, a relatively constant level throughout the Subalpine Basin contains an abundant ammonite fauna, dominated by Perisphinctinae. The Oppeliidae are still frequent, with *Taramelliceras episcopalis* de Loriol. We can note the last appearance datum of *Perisphinctes picteti* de Loriol. Some *Cardioceras praemartini* Spath indicate the base of the Praecordatum Subzone.

At the top, in the western and south-western parts of the basin, it is possible to find *Peltoceratoides williamsoni* (Phillips) and *Cardioceras praecordatum* Douvillé.

*** Cordatum Zone** (d'Orbigny, 1852; Levels 11 and 12 *in* Fortwengler, 1989; Fortwengler & Marchand, 1994a-b).

Near Sahune, the Cordatum zone is about 120 m thick (Pellenard, 2003). In the majority of the sections studied, the upper part of the Terres Noires Fm contains fauna characteristic of the Cordatum Zone, sometimes rich in Cardioceratinae.

At the base, the Cardioceratinae are morphologically very close to *Cardioceras bukowskii* Maire (Level 11; Bukowskii Subzone). In the Baronnies, the western Diois and the district of Sisteron, as well as on the Ardèche margin, they are abundant and accompanied by *Cardioceras korys* (Buckman) (Fortwengler, 1989; Marchand et al., 1990; Marchand & Fortwengler, 2010).

The uppermost part still contains a fauna of the Cordatum Subzone (Level 12), with *Cardioceras persecans* Buckman. However, Level 12 is poorly individualised and contains rare *Cardioceras cordatum* (Sowerby) with a fauna dominated by the *Sowerbyceras* genus.

Middle Oxfordian p.p.

The final sedimentary unit of the Terres Noires Fm is 80 to 180 m thick and less fossil-rich than the lower units (Pellenard, 2003). It is however possible to recognise two faunal assemblages, corresponding to the Vertebrale Subzone and to the Antecedens Subzone of the Plicatilis Zone.

*** Plicatilis Zone** (Hudleston, 1878; Levels 13 and 14 *in* Fortwengler, 1989; Fortwengler & Marchand, 1994a-b).

In the lower part, which corresponds to the Vertebrale Subzone, the Cardioceratinae are small, and could be confused with those of the Cordatum Subzone. Note the first appearance datum of *Protophites christoli* (Beaudoin).

The marls just below the thick Argovian marl/limestone alternation facies are characterised by the first appearance datum of *Taramelliceras dentostriatum* (Quenstedt). The Cardioceratinae are very rare, but their morphology is that of the Antecedens Subzone species.

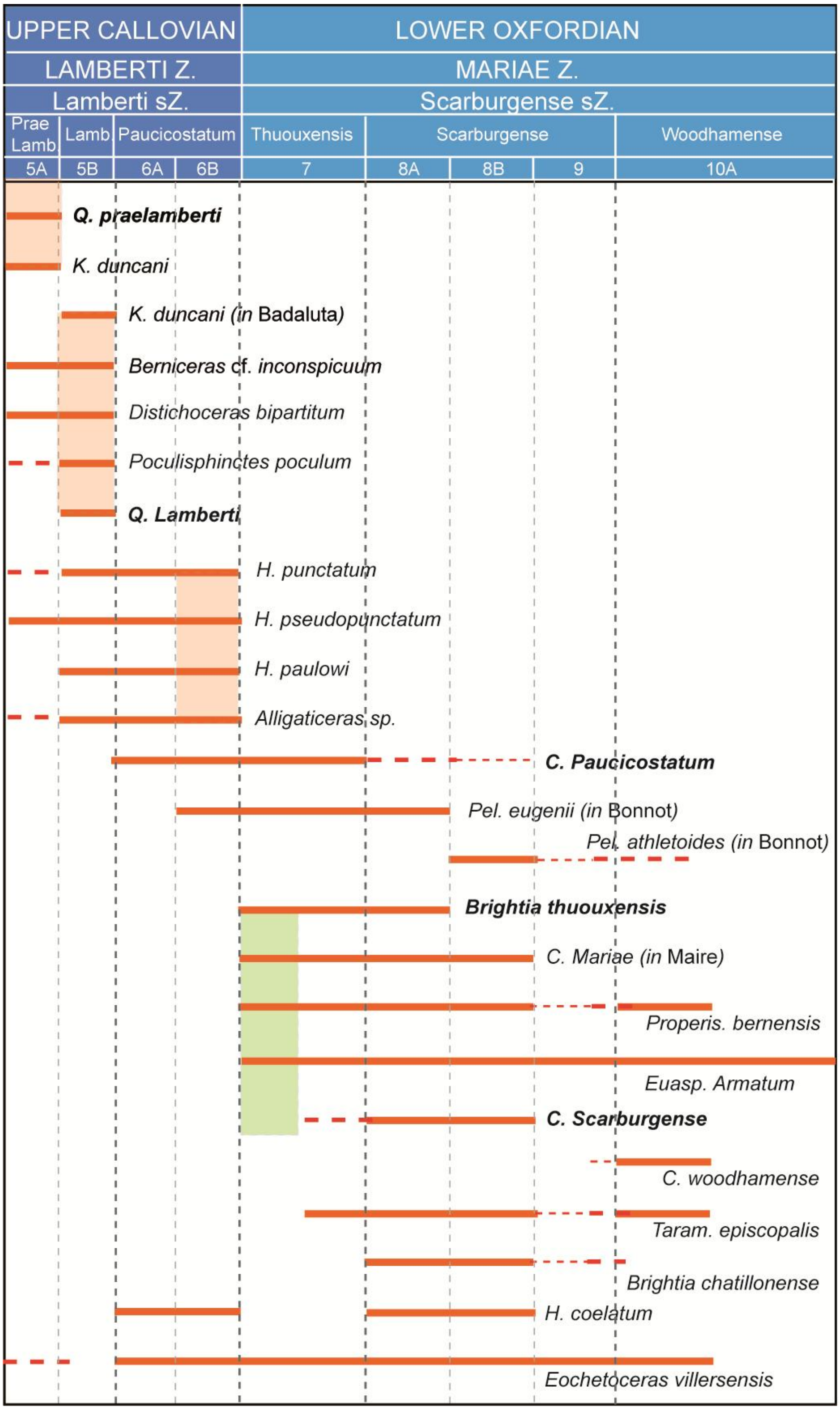


Figure 11: Stratigraphic range of the major ammonite species found in Levels 5A to 10A of the Terres Noires Fm at the Callovian-Oxfordian boundary. Subsequent chronostratigraphic levels and biostratigraphic zonal scheme are based on first and last appearance of ammonite taxa and faunal ammonite associations. Genera and species of the ammonite subfamilies Cardioceratinae and Hecticoceratinae are based on: 1) their relative abundance; 2) their progressive southward extension during the Callovian, from the Boreal/Sub-Boreal Realm to the Sub-Mediterranean/Tethyan Realm; 3) the rapid and consistent succession of species, identified by their remarkable morphological evolution. Red boxes: major disappearance,

green box: major appearance.

Nannofossil biostratigraphy

The transition from the Lamberti to the Mariae zones is marked by a succession of first and last occurrences (FO and LO) of nannoplankton species, whose calibration and correlation potential has remained somewhat limited, due to provincialism, the dominance of siliceous sedimentation and the presence of hiatuses in southern Tethys sections. In recent biostratigraphic syntheses, the main nannoplankton biohorizons for the Callovian-Oxfordian boundary are: the LO of Ansulasphaera helvetica (lower part of the Lamberti Zone; Bown et al., 1988; de Kaenel et al 1996) and the total range (FO and LO) of Stephanolithion bigoti maximum, reported from the uppermost part of the Lamberti to the Cordatum zones in NW Europe (Bown et al., 1988) and from the uppermost part of the Lamberti to the Mariae zones in SE France (Fauconnier et al., 1996; de Kaenel et al 1996; Giraud et al., 2009). Competing correlations for this nannofossil biohorizon, if not related to proven diachroneity or low resolution sampling, could also be caused by the discrepant application of taxonomic concepts.

The potential of nannofossil biohorizons as useful proxies for the Callovian-Oxfordian boundary has been tested in the Thuoux, Savournon and Saint-Pierre d'Argençon sections (see Figs. 21 & 33). Calcareous nannofossils were investigated in smear slides at high resolution with an optical microscope at 1250X. All the samples studied yielded few to abundant nannofossil assemblages, of moderate to poor preservation, with a species richness of about 30 species. The assemblages are dominated by *Watznaueria britannica* morphotypes (Giraud et al 2009) at 75%, followed by quite abundant *W. fossacincta, Zeugrhabdotus erectus, Discorhabdus*, Podorhabdids and common *Stephanolithion bigotii*.

Sporadic A. helvetica and Stephanolithion hexum were observed in the lowermost part of the Saint-Pierre d'Argençon section (pre-Lamberti Zone), making it difficult to fix a reliable LO biohorizon. The sub-species Stephanolithion bigoti maximum was originally described as having "overall measurements exceeding 6 µm" (MEDD, 1979); therefore all the S. bigoti encountered were accurately measured. Biometric measurements revealed that large-sized S. bigoti, i.e. reaching a maximum rim length of 5.80 µm (Fig. 12), are recorded from the Paucicostatum Subzone in the three sections, roughly coinciding with the beginning of a positive carbon isotope shift at Thuoux and Savournon. This size increase is clearly visible to the eye, yet no specimen reaching/exceeding 6 µm, classified as S. bigoti maximum, was measured in the uppermost Callovian sediments of the three sections. Thus, S. bigoti maximum is absent in the uppermost Callovian sediments and this is confirmed elsewhere in other Callovian-Oxfordian sections in SE France (Jonquière, Quissac; Gardin, unpublished), where this sub-species occurs only in Lower Oxfordian samples, from the Precordatum Subzone (Fig. 12).

To conclude: 1) the recognition and utility of S. bigoti maximum as a marker for dating and correlating the Callovian-Oxfordian boundary depends essentially on accurate biometric measurements. 2) It is possible that the FO and LO of this subspecies could be diachronous between the Boreal and Tethyan realms, although miscalibration of samples with respect to ammonite zones, reduced carbonate sedimentation and hiatuses in southern sections should also be taken into account. 3) The net size increase of S. bigoti across the Callovian-Oxfordian boundary observed in the southern French sections, if not well constrained by accurate measurements, might be erroneously interpreted as the FO of genuine S. bigoti maximum, thus generating confusion in the calibration and correlation of this biohorizon.

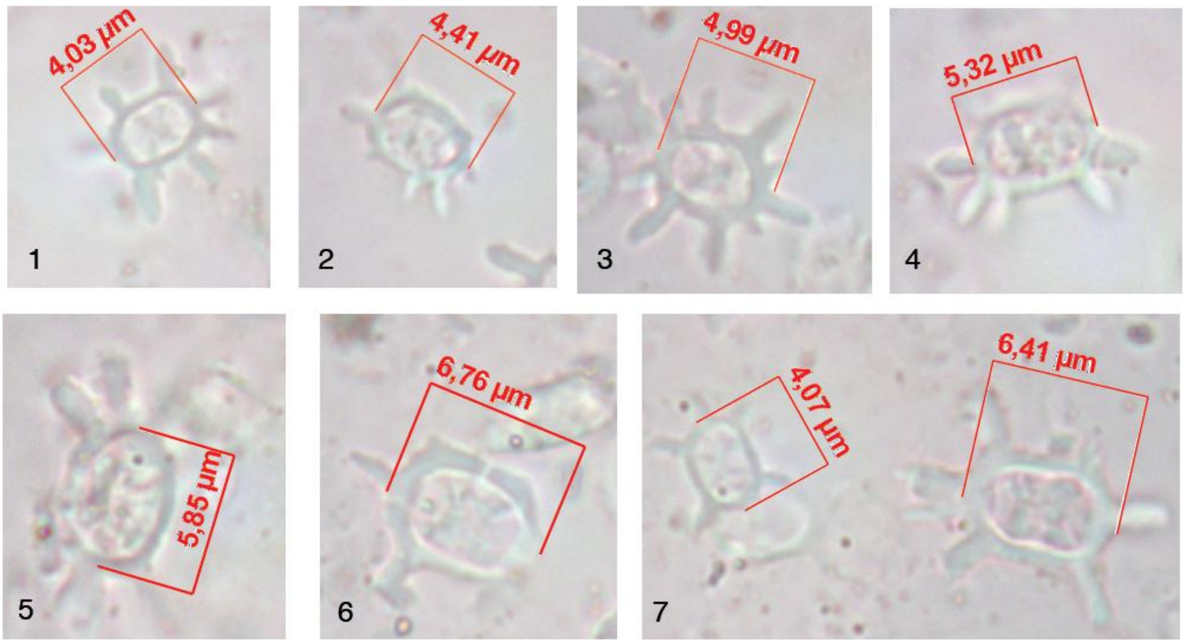


Figure 12: Figure 1. Biometric measurements performed on Stephanolithion bigoti specimens from the sections studied. All micrographs were taken with an optical microscope without polarizers. Scale is reported on each micrograph.

1.1. - Stephanolithion bigoti bigoti, sample AE 480, St Pierre d'Argençon section

1.2. - Stephanolithion bigoti bigoti, sample TH 19, Thuoux section

1.3. - Stephanolithion bigoti bigoti, sample TH 39, Thuoux section

1.4. - Stephanolithion bigoti bigoti, large-size specimen, sample SAV 17c, Savournon section

1.5. - Stephanolithion bigoti bigoti, large-size specimen, sample SAV 23.1, Savournon section

1.6. - Stephanolithion bigoti maximum, sample 56V, Jonquière section

1.7. - Stephanolithion bigoti bigoti and Stephanolithion bigoti maximum, sample 56V, Jonquière section

Dinoflagellate, foraminifer and ostracod biostratigraphy

A previous study by Poulsen and Jutson, (1996) showed that most of the stratigraphically important dinoflagellate species are present in the faunal assemblages. It confirmed that *Durotrigia filapicata* Gocht disappeared at the top of the Callovian, while some rare *Wanaea fimbriata* Sarjeant appeared at the base of the Oxfordian, as also observed in the North Sea Region and in East Greenland. New data is currently under analysis for Thuoux and Saint-Pierre d'Argençon (see p.44 and p.62).

Poulsen and Jutson, (1996) also indicate that foraminifers were poorly preserved. Only two stratigraphically significant species have been identified: *Ophthalmidium compressum* Ostenfeld and *O. strumosum* Gümbel *O. compressum* disappeared during the *thuouxensis* Biohorizon when it was replaced by *O. strumosum*, which appeared during the *paucicostatum* Biohorizon, persisting into the *scarburgense* Biohorizon. New data is currently under analysis for the Thuoux and Savournon sections.

Preliminary research shows that ostracods are rare but nevertheless observed at Savournon (Tesakova, 2008). New data is currently under analysis for the Thuoux and Saint-Pierre d'Argençon sections.

Field trip1: The Saint-Pierre d'Argençon/Aspres -sur-Buëch section

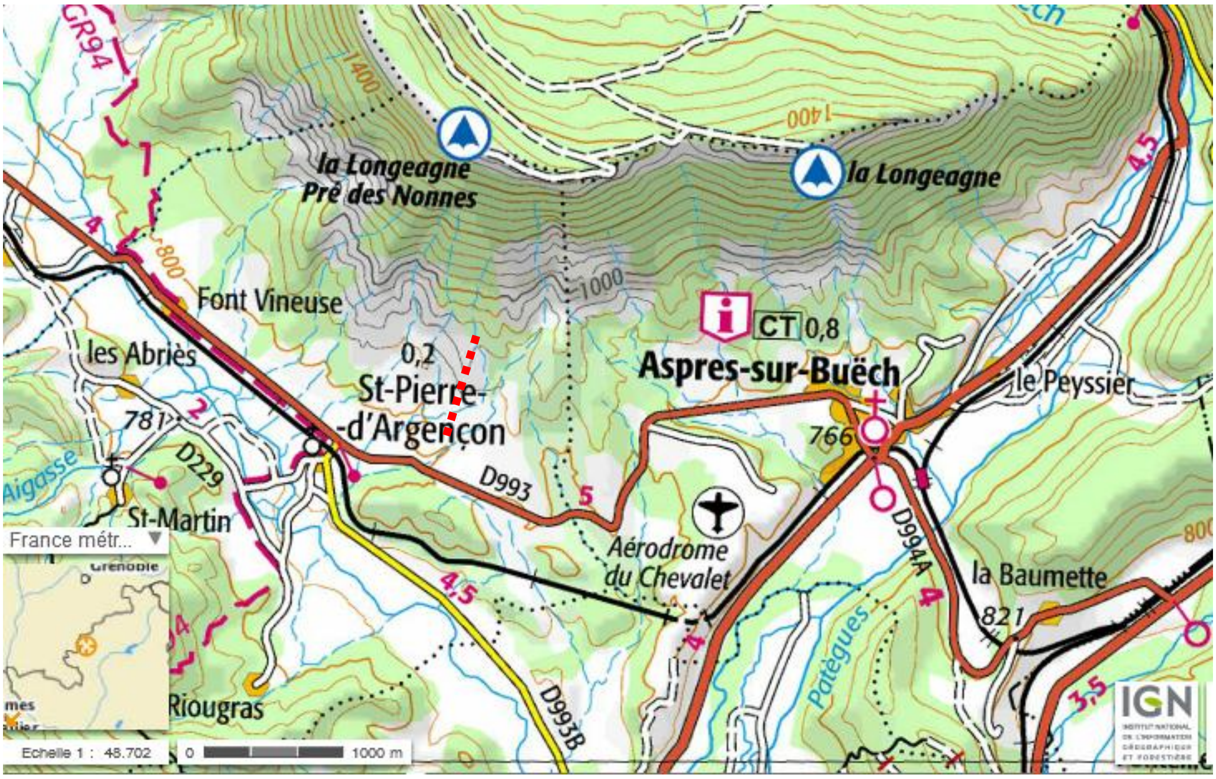


Figure 13: The Saint-Pierre d'Argençon-Le Gravas outcrop (dashed red line).

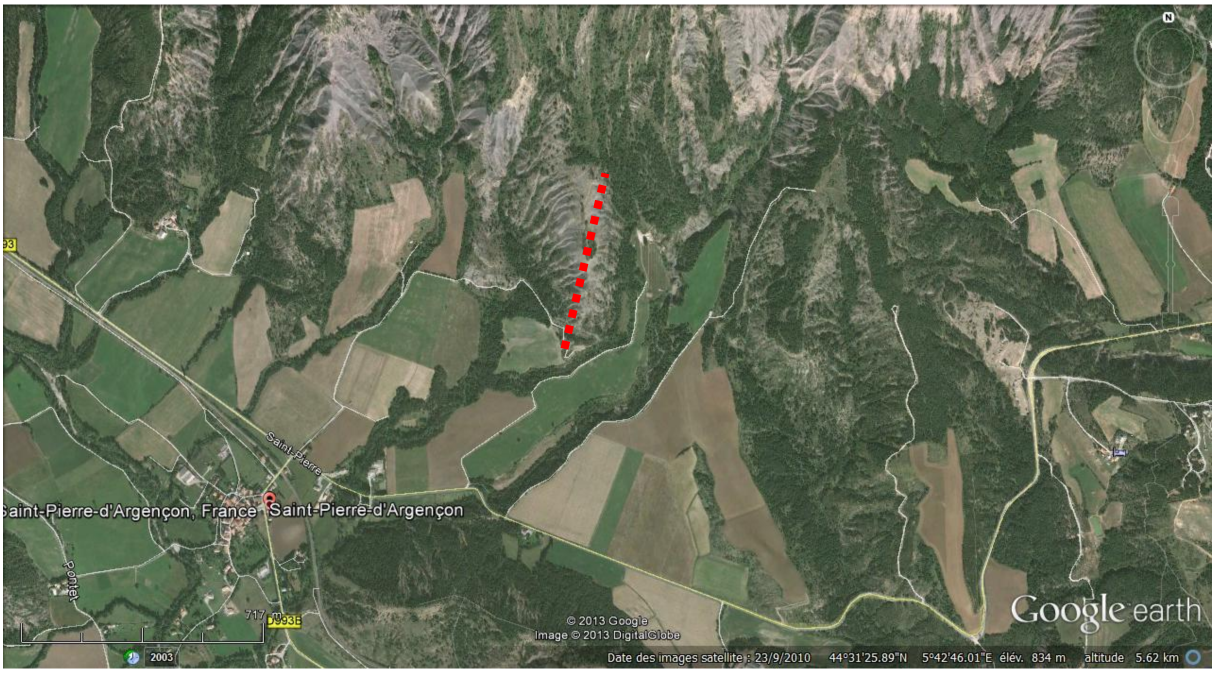


Figure 14: Aerial photograph of the Saint-Pierre d'Argençon-Le Gravas outcrop (dashed red line).

The Terres Noires Fm at Saint-Pierre d'Argençon/Aspres-sur-Buëch covers a stratigraphic interval encompassing Levels 4 to 10A in the Thuoux and Savournon sections (Gaspard 2005; Huret 2006; Boulila *et al*., 2008; Fortwengler *et al*., 2012). From base to top, they extend from the Upper Callovian (Lamberti Zone, Lamberti Subzone, *henrici* Biohorizon) to Middle Oxfordian (Transversarium Zone) interval (Fig. 15).

- Levels 4 to 5B: composed of about 60 m of grey marls. Several thin calcareous intercalations, 1 m thick, which stand out due to weathering are found in the upper part (top of Level 4 and base of Level 5B). Whatever the level, orange-ochre nodules are quite frequent; some of them show laminae interpreted as tempestite storm deposits (Fig. 16d). Abundant, diversified ammonites allow precise attribution to Levels 4 to 5B (Lamberti Zone, Lamberti Subzone, *praelamberti* and *lamberti* biohorizons).

- Levels 6 to 8B: about 40 m thick, with soft marls, generally softer in the lower part than in the upper part. Like Levels 4A and 5B, they show alignments of orange-ochre or rusty nodules with frequent laminae. They cover the stratigraphic interval of the Callovian-Oxfordian boundary (Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon to Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon).

- Levels 9 and 10A: a thick series (109m) of marls, harder than the lower levels. They contain two metre-thick intercalations of calcareous nodules. Except near the top of Level 10A with a level of greenish phosphatic nodules (Fig. 16e), these marly sediments contain large platy nodules and smaller nodule intercalations, similar to the lower levels. (Level 9: Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon; Level 10A: Mariae Zone, Scarburgense Subzone, *woodhamense* Biohorizon).

In the Saint-Pierre d'Argençon section, the Upper Callovian/Lower Oxfordian transition is located at the boundary between lithological Levels 6B and 7, within a homogeneous thick marly series. The Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon and the Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon are clearly and precisely recognised by their characteristic ammonite assemblages.

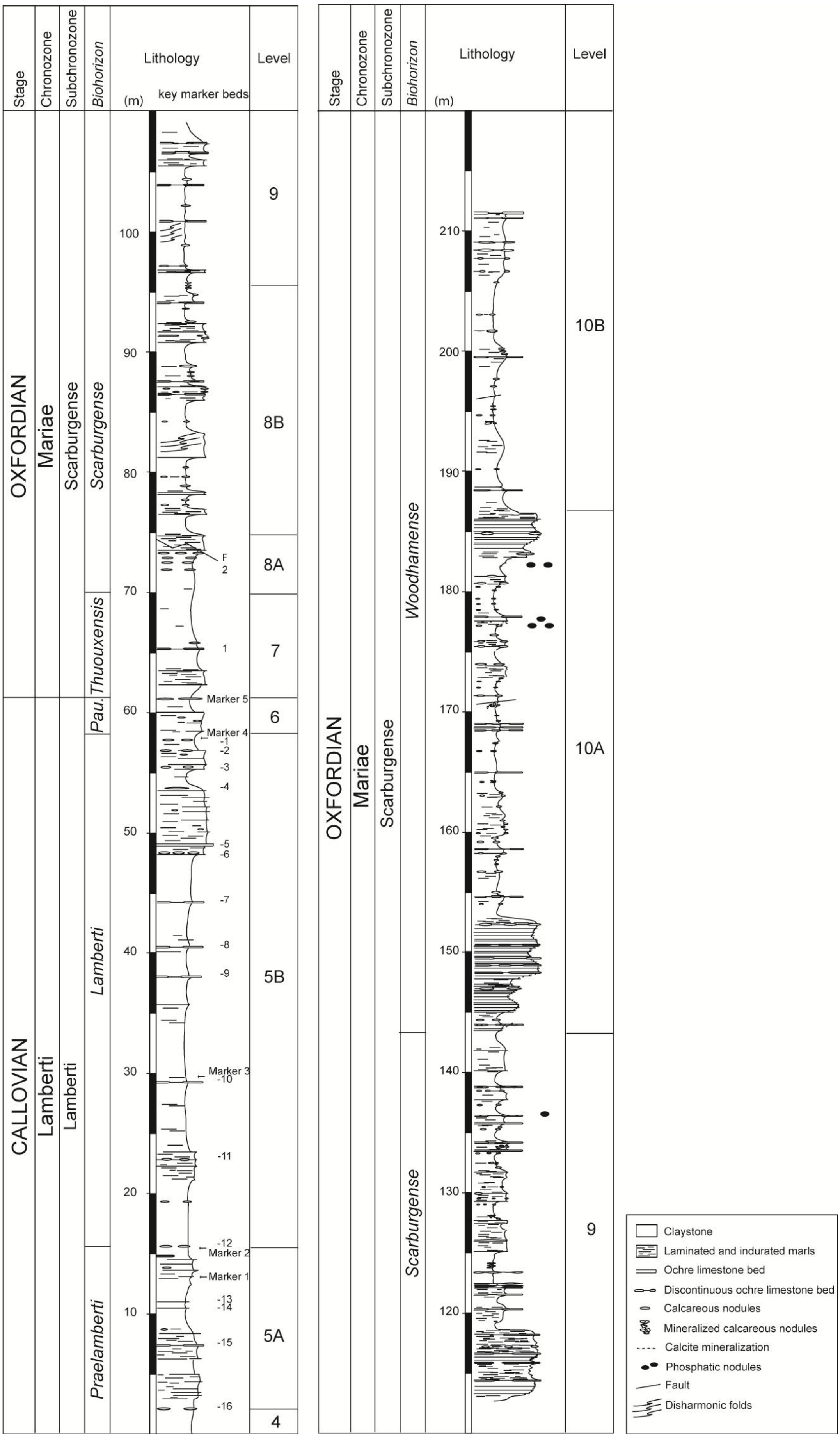


Figure 15: Biostratigraphy, lithology and facies of the Terres Noires Fm at Saint-Pierre d'Argençon.

Figure 16: Photographs of the Saint-Pierre d’Argençon showing a: general view of outcrops, b, c: area of the Callovian/Oxfordian boundary, d: calcareous nodule with visible laminae, interpreted as a distal tempestite, e: greenish phosphatic nodules with traces of boring.

The fossil record

Ammonites

* UPPER CALLOVIAN

- Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon (Hébert, 1857 *emend*.

Marchand, 1986; base of Level 5 *in* Fortwengler, 1989; base of *lamberti* Biohorizon (Level 5A) *in* Fortwengler *et al.,* 1997).

Marls at the base of the slope are dated by numerous *Quenstedtoceras praelamberti* Douvillé (35%), found with *Hecticoceras pseudopunctatum* Lahusen. Among the Phylloceratina (23%), the genus *Sowerbyceras* is highly dominant.

- Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon (Hébert, 1857 *emend*. Marchand, 1986; upper part of Level 5 *in* Fortwengler, 1989; Level 5B *in* Fortwengler *et al.*, 1997).

Unlike the previous level, Level 5B has an outstanding fossil record; ammonites, often large and epigenised in calcite or barite, are well preserved.

As in the Thuoux section, Cardioceratinae are very rare, but the spectral fauna and the ammonite assemblages are typical of the *lamberti* Biohorizon. Perisphinctidae, mainly *Poculisphinctes poculum* (Leckenby) and large *Alligaticeras sp*., (41%) are still dominant, but slightly less so than at Thuoux. Hecticoceratinae (20 %) are better represented and more diversified than at Thuoux: *Putealiceras punctatum* (Stalh) and *Orbignyceras paulowi* (de Tsytovitch). Surprisingly, a Peltoceratinae with clearly duplicated latero-ventral tubercles has been collected; this association is very rare. The rest of the ammonite fauna is exactly the same as at Thuoux, with the following taxa: *Euaspidoceras subbabeanum* (Sintzow), *Pachyceras sp*., *Berniceras cf. inconspicuum* (de Loriol), *Sowerbyceras tortisulcatum* (d'Orbigny) and *Holcophylloceras mediterraneum* (Neumayr).

- Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon (Marchand, 1979, *emend*. Fortwengler & Marchand, 1994; Level 6 *in* Fortwengler, 1989 and Fortwengler et *al.*, 1997).

At Saint-Pierre d'Argençon, *Cardioceras paucicostatum* Lange is found just above a well-marked thin limestone bundle. The population contains individuals with "primitive" (*in* Debrand-Passard *et al*., 1978, pl. 1, fig. 9 & 10) and "advanced" (*in* Fortwengler *et al*., 1997, fig. 6.8) morphologies, which clearly indicate the *paucicostatum* Biohorizon. The genus *Peltoceratoides* has not been found in the upper part of the level. The *Pseudoperisphinctinae* and *Hecticoceratinae* are the same as at Thuoux.

* LOWER OXFORDIAN

- Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon (Fortwengler et *al.*, 1997; *elisabethae* Biohorizon, Fortwengler & Marchand, 1994; Level 7 *in* Fortwengler, 1989).

The Callovian Hecticoceratinae are no longer found above the boundary between Level 6 and Level 7 (Callovian-Oxfordian boundary).

Both the *paucicostatum* Biohorizon (Level 6) and the *thuouxensis* Biohorizon (Level 7) are thinner than at Thuoux, so ammonites are less abundant, but with the same assemblages, and smaller phosphatic ammonites. There are more Cardioceratinae and fewer Peltoceratinae (19%), and some Phylloceratinae (13%).

- Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon (Buckman 1913, *emend*. Fortwengler & Marchand, 1994; Levels 8 and 9 in Fortwengler, 1989 and Fortwengler *et al.*, 2012).

Levels 8A and 8B: Fewer ammonites have been collected from these thinner levels, but the faunal turnovers also observed at Thuoux are all present: the first appearance datum of *Hecticoceras (Brightia) chatillonense* de Loriol (Level 8A), followed in Level 8B by the replacement of *Peltoceratoides eugenii* Raspail by *Peltoceratoides athletoides* (Lahusen). The remaining fauna is identical to that at Thuoux.

Level 9: The marly deposits of this level, slightly richer than at Thuoux, crop out well at Saint-Pierre d'Argençon. Despite poor fossilisation due to disharmonic folds, a diversified assemblage has been collected: *Eochetoceras villersensis* (d'Orbigny), *Lytoceras fimbriatum* Sowerby, *Lissoceras erato* d'Orbigny, *Properisphinctes bernensis* de Loriol, *Sowerbyceras tortisulcatum* d'Orbigny, and *Holcophylloceras mediterraneum* (Neumayr).

- Mariae Zone, Scarburgense Subzone, *woodhamense* Biohorizon (Fortwengler & Marchand, 1991, 1994; uppermost part of Level 9 *in* Fortwengler, 1989; Level 10A *in* Fortwengler et *al.*, 2012).

Level 10A: Because of the steep slope in the upper part of the outcrop, it has proved difficult to collect ammonites in continuity with the previous levels. However, several parallel and contiguous outcrops can be substituted as complementary sections for Level 10A.

The ammonite fauna is diversified, very similar to that of Thuoux, characterised by a consistent enrichment in Perisphinctinae and fewer Phylloceratinae. The lower part of this level, Level 10A1, is fossil-rich, with well-preserved ammonites, similar to Thuoux, but clearly different from Savournon, where there are fewer Perisphinctinae and more Phylloceratinae. The biohorizon index species, *Cardioceras (Scarburgiceras) woodhamense* Arkell has been found here, but it is very rare.

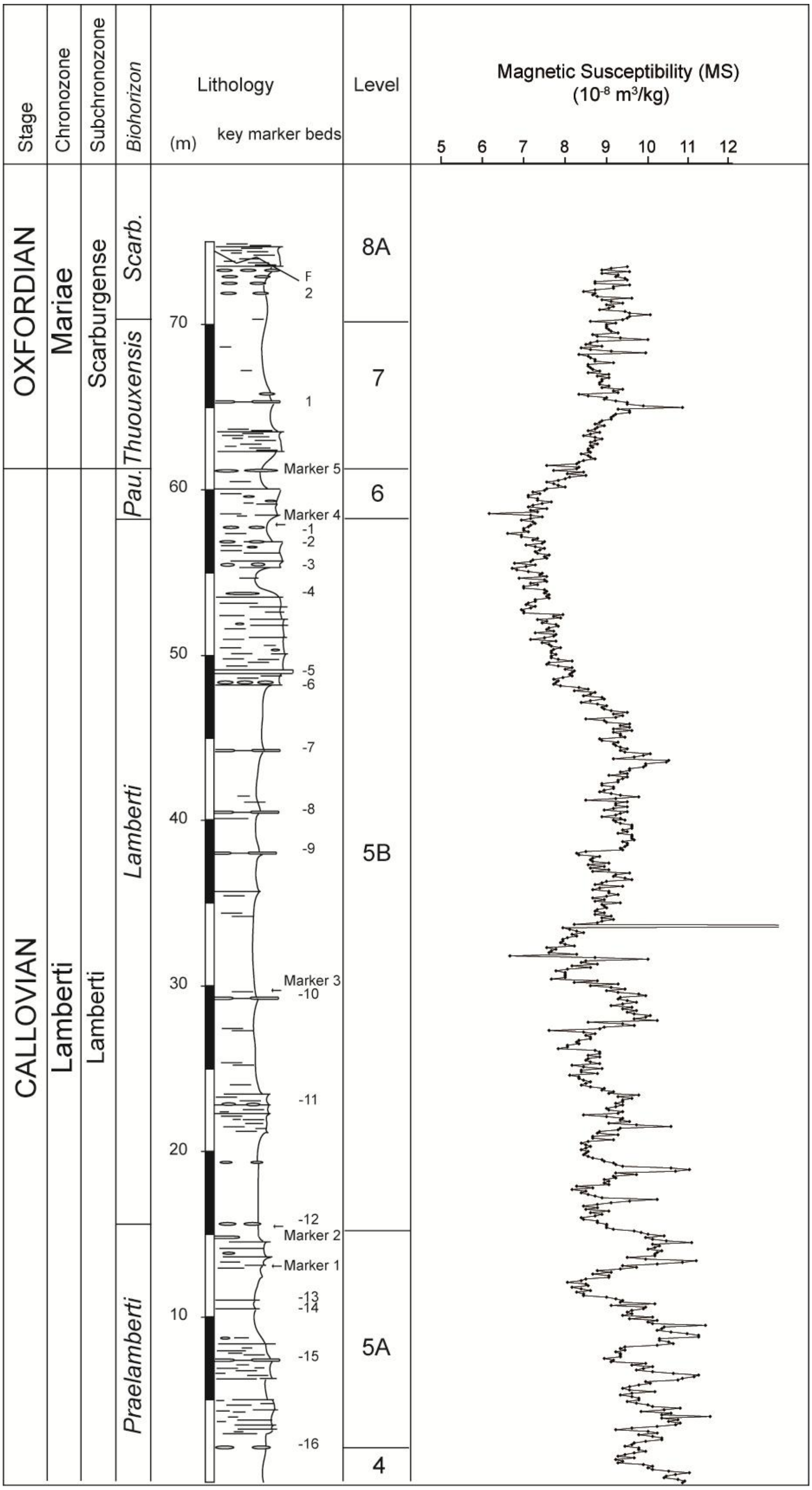


Figure 17: Detailed magnetic susceptibility (MS) for the Saint-Pierre d'Argençon section

Physical stratigraphy (magnetic susceptibility)

In the Saint-Pierre d'Argençon section, we sampled about 73 m of an interval spanning the Callovian-Oxfordian boundary (Henrici *p.p.*, Lamberti and Scarburgense *p.p.* Subzones (Fig. 17). The sampling step was fixed at 10 cm, resulting in 735 samples (Fig. 17). The 735 samples collected were measured for magnetic susceptibility (MS) with a Kappabridge susceptometer MFK-1. Each sample was measured three times, and the mean of these values is reported after weight normalisation. The standard deviation of the analytical error associated to the MS measurements, based on triplicate analyses, is 0.0091×10^{-8} m^3/kg.

The MS values are relatively low (ranging from 6.5 to 11.5×10^{-8} m^3/kg) and their variations follow a strongly cyclical pattern (Fig. 17). There are short-wavelength cycles superimposed on a long-wavelength cycle, to be studied in detail later.

Field trip 2: The Thuoux section

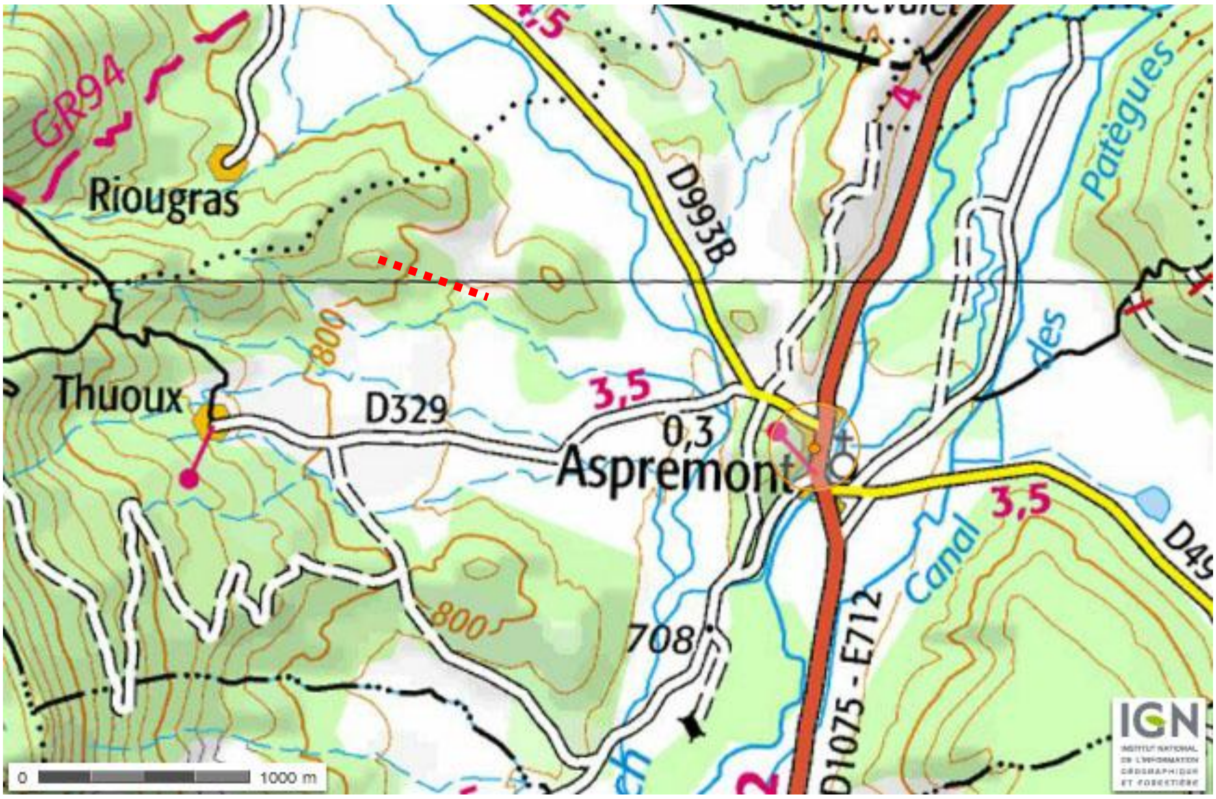


Figure 18: The Thuoux-Les Lamberts outcrop (dashed red line)

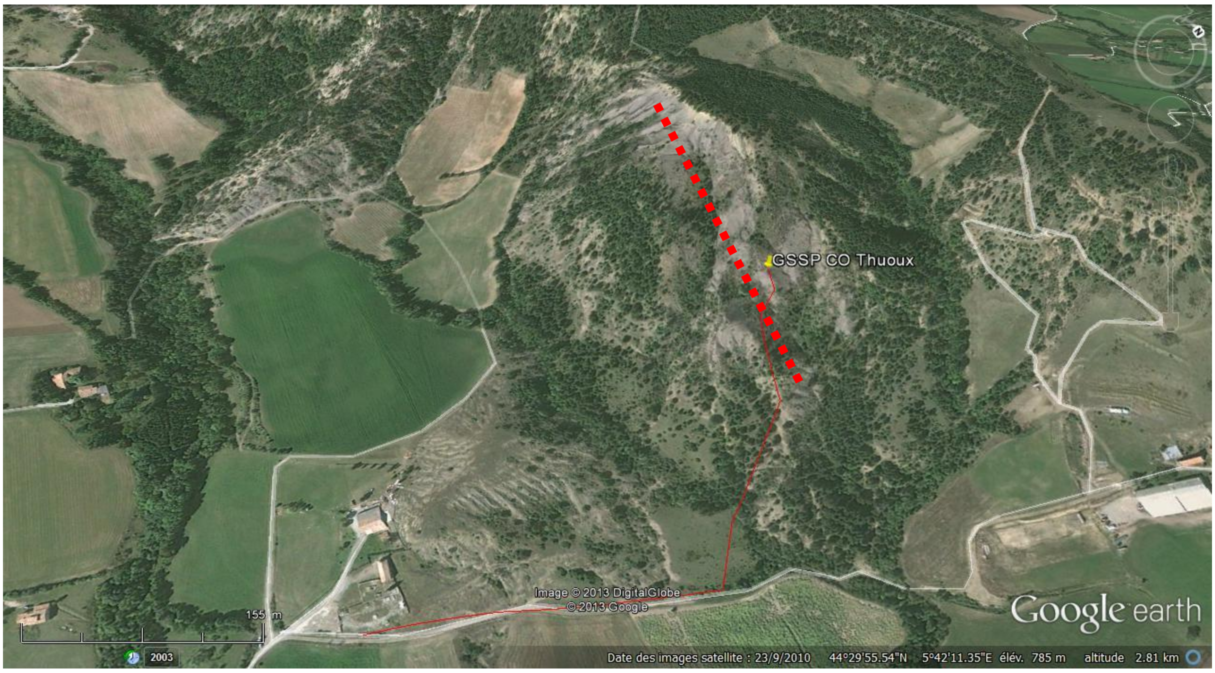


Figure 19: Aerial photograph of the Thuoux-Les Lamberts section with position of the Callovian-Oxfordian boundary (coordinates 44°30'0.84"N latitude, 5°42'13.05"E longitude)

Only the interval encompassing the Callovian-Oxfordian boundary (from Level 5B to Level 10A), is described here, with around 80 m of marly sediments, from the late Upper Callovian (Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon) to the base of the Lower Oxfordian (Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon, Fig. 21). In this section, the boundary between the Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, and the Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon, is clearly and precisely located at the boundary between Level 6B and Level 7 (Fortwengler, 1989; Fortwengler & Marchand, 1994d; Fortwengler *et al*., 1997, 2012).

- Level 5B: around 9 m of dark grey marls, with some grey calcareous nodules, occasionally large and platy; Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon.

- Level 6: around 15 m of softish, grey marls, with small grey nodules and thin, harder clayey limestone intercalations. The progressive transition between the upper part of Level 5B and Level 6 is marked by more frequent thin, calcareous levels. Calcareous and mineralised concretions are abundant in the upper part of Level 6, which can be divided into Level 6A (11m) and Level 6B (6m); Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon.

- Level 7: around 13 m of yellowish marls with numerous intercalations of aligned rust-to-ochre large platy nodules at the base; Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon.

- Level 8A: around 6 m, with 3 m of more calcareous marls. This level also contains aligned large rust-to-ochre lenticular platy nodules, particularly rich in ammonites, with laminae interpreted as distal tempestite storm deposits, and discrete erosional surfaces; Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon.

- Level 8B: after 3 m of more calcareous marls, around 13 m of fairly homogeneous marls, with calcareous and mineralized concretions; pyritous nodules are interbedded in soft marls at the top; Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon.

- Level 9: around 17 m of homogeneous light grey marls, interbedded with rust-to-ochre calcareous bundles with large platy nodules and rare pyritous nodules; Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon.

- Level 10A: about 15 m of soft darker marls with grey nodules and, locally, small greenish phosphatic nodules; Mariae Zone, Scarburgense Subzone, *woodhamense* Biohorizon.

Figure 20: Photographs of the Thuoux section showing a: a general view of the outcrop, b: the position of the Callovian-Oxfordian boundary, c: field gamma-ray measurements are facilitated by the stratigraphy and sparse vegetation.

The fossil record

Ammonites

Only the Lamberti-Mariae zones and their subdivisions (subzones and biohorizons) immediately surrounding the Callovian-Oxfordian boundary are described here.

* UPPER CALLOVIAN

\- Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon (Hébert, 1857 *emend*. Marchand, 1986; top of Level 5 *in* Fortwengler, 1989; Level 5B *in* Fortwengler et *al.*, 1997).

In the marly deposits at the base of the section, no characteristic fossils have been found. Towards the top of this level, large calcareous nodules contain abundant, often large ammonites. The inner whorls of these ammonites are sometimes made of calcite and barite, favouring good fossilisation. The Perisphinctidae (over 50%) are mainly *Alligaticeras sp*. and *Poculisphinctes poculum* Leckenby, macroconchs and microconchs. *Quenstedtoceras*, which was abundant in the *praelamberti* Biohorizon becomes very rare (3%). The ribbing of the *Quenstedtoceras praelamberti* Douvillé changes significantly, with thicker primaries and more intercalaries, very similar to *Quenstedtoceras lamberti* (Sowerby) *in* Douvillé 1912.

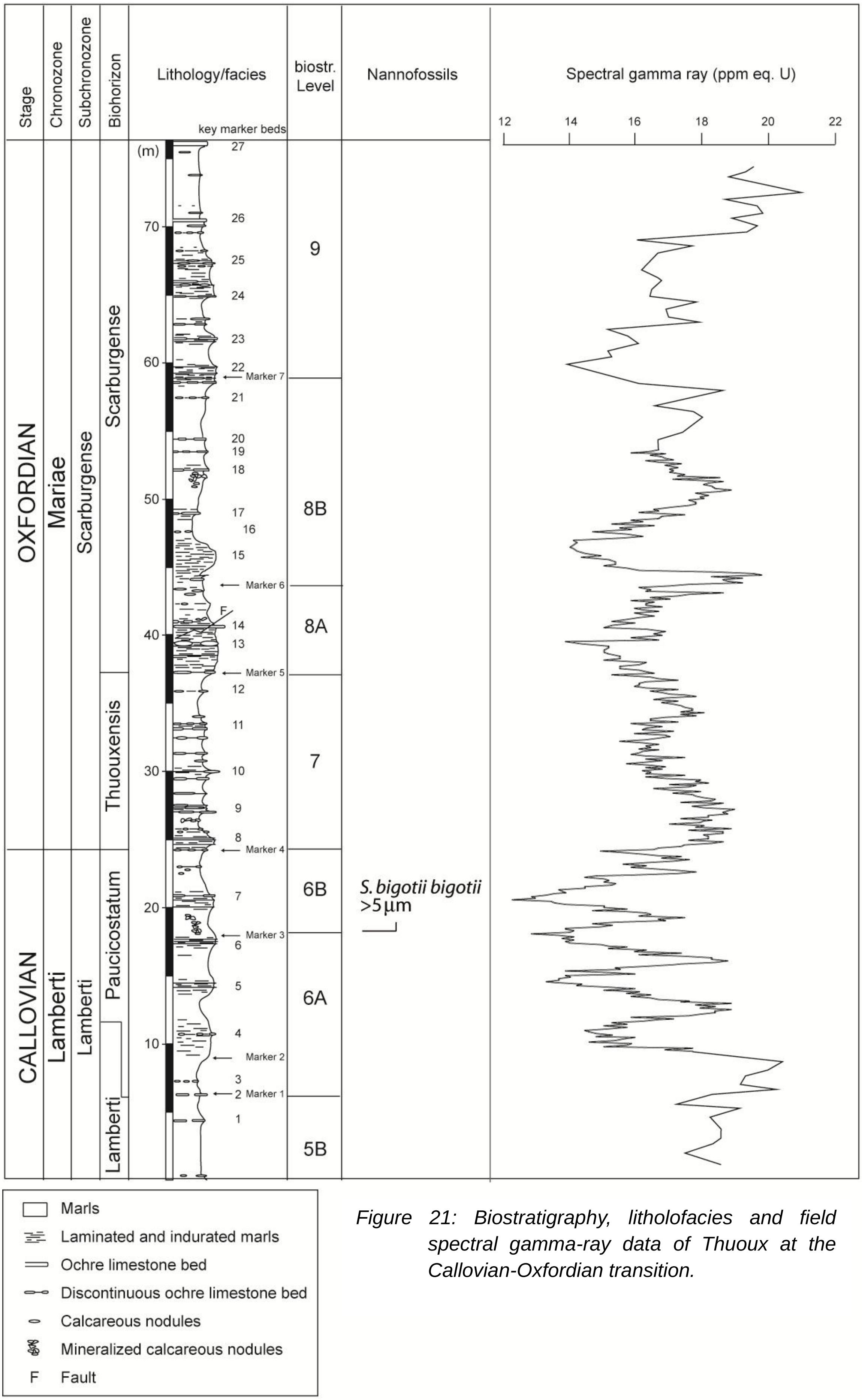


Figure 21: Biostratigraphy, litholofacies and field spectral gamma-ray data of Thuoux at the Callovian-Oxfordian transition.

The Oppeliidae are also less abundant (8%), mainly *Hecticoceras (Putealiceras*) *pseudopunctatum* Lahusen, with the last few specimens of Kosmoceratidae (*Kosmoceras duncani* Sowerby *in* Badaluta, 1976), *Distichoceras sp.* and *Bernicera*s *sp*. The Phylloceratinae are slightly more frequent (16%) than in the lower layers. The remaining ammonite fauna contains rare *Lissoceras sp*. and *Euaspidoceras subbabeanum* (Sintzow).

- Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon (Marchand, 1979, *emend*. Fortwengler & Marchand, 1994; Level 6 *in* Fortwengler, 1989 and Fortwengler *et al.*, 1997).

In the Thuoux section, this interval is highly fossiliferous and thick enough to be divided into two. The interbedded harder and softer marls produce favourable field topographic conditions for fossil collection. The ammonites found in calcareous nodules are rather small, and often fragmented, but their morphology and ornamentation is well preserved.

A new species of Cardioceratidae, *Cardioceras paucicostatum* (Lange) appears near the base (Level 6A, Fortwengler *et al.*, 1997); several variants of the population are morphologically very close to *Quenstedtoceras lamberti* (Sowerby). The Hecticoceratinae represent more than half of the total ammonite fauna; mainly the typical Callovian species present in Level 5B: *Hecticoceras* (*Putealiceras) punctatum* (Lahusen), *Hecticoceras (Putealiceras) pseudopunctatum* (Lahusen), *Hecticoceras* (*Orbignyceras) paulowi* (de Tsytovitch). The Perisphinctidae, represented by *Alligaticeras sp.* and *Orionoides sp.*, are far less abundant (6%).

Such general trends in the uppermost Callovian ammonite associations are confirmed in the upper part of Level 6B, but the faunal assemblage is considerably modified by the sudden appearance of *Peltoceratoides eugenii* Raspail (19%; Bonnot, 1995; Bonnot *et al.*, 1997). *Euaspidoceras subbabeanum* (Sintzow) is still present. Some rare individuals with the "primitive" morphologies of *Cardioceras paucicostatum* (Lange) are still found in Level 6B.

The Phylloceratinae become more abundant in the ammonite faunal associations (23-25%), but this proportion is still quite low for the palaeoenvironmental context of the Terres Noires Fm.

* LOWER OXFORDIAN

- Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon (Fortwengler *et al.*, 1997; *elisabethae* Biohorizon, Fortwengler & Marchand, 1994; Level 7 *in* Fortwengler, 1989).

Following the total and concomitant disappearance of the Callovian Hecticoceratidae - *Hecticoceras pseudopunctatum* Lahusen, Hecticoceras *punctatum* Lahusen, Hecticoceras *paulowi* (de Tsytovitch) - new ammonite species appear, in particular among the Oppeliidae with *Hecticoceras* (*Brightia) thuouxensis* Fortwengler & Marchand. This new taxon is very frequent (33%) from the base of Level 7. Its characteristic morphology differentiates it from the Oppeliidae of the underlying levels. *Hecticoceras* (*Brightia) thuouxensis* Fortwengler & Marchand has prominent umbilical tubercles and soft ribbing due to the presence of intercalaries. The population is morphologically homogeneous, with very rare, stronger-ribbed "variants". The genus *Taramelliceras*, which was almost absent from the Callovian Terres Noires Fm, is found again in the *thuouxensis* Biohorizon, with some *Taramelliceras episcopalis* (de Loriol).

The Perisphinctidae experienced a similar species renewal to the Oppeliidae. The Callovian Pseudoperisphinctinae disappear and the *Alligaticeras* are replaced by rare *Properisphinctes bernensis* de Loriol. At the same time, *Peltoceratoides eugenii* (Raspail) remains morphologically stable and becomes very abundant (38%). Additionally, the first appearance datum of *Euaspidoceras armatum* (de Loriol) is in the *thuouxensis* Biohorizon.

Cardioceratinae remain infrequent (10%). *Cardioceras paucicostatum* (Lange) acquire dense, fine lateral ribs, abandoning the "primitive" morphology found in Level 6. Phylloceratinae, which have been present since the *praelamberti* Biohorizon, are only moderately abundant in the Terres Noires Fm (21%, as in the *paucicostatum* Biohorizon).

A possible Level 7B interval is found in the upper part of the biohorizon, characterised by rare Cardioceratinae and more abundant Aspidoceratinae.

- Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon (Buckman 1913, *emend*. Fortwengler & Marchand, 1994; Levels 8 and 9 in Fortwengler, 1989 and Fortwengler *et al.* 1997, 2012).

Differences in ammonite faunal associations clearly indicate three levels (8A, 8B and 9) for this biohorizon.

<u>Level 8A</u>: The base of the *scarburgense* Biohorizon crops out well in the network of ravines in the Thuoux-les Lamberts section. It is more fossiliferous in its marly eastern part than in the west, where ammonites are mainly found in calcareous concretions.

Brightia thuouxensis Fortwengler & Marchand becomes less frequent, generally replaced by *Brightia chatillonense* de Loriol, with much less ornamentation on the macroconch. Changes occur in the Cardioceratinae: in addition to *Cardioceras paucicostatum* Lange, identical to the "advanced" variants found in lower levels, many specimens can be determined as *Scarburgiceras scarburgense* Young & Bird.

The complementary fauna is very similar to that of Level 7 (*Thuouxensis* Biohorizon), but with the first appearance datum of *Eochetoceras coelatum* Coquand in the Oxfordian. *Properisphinctes bernensis* de Loriol becomes a little more abundant. *Rollieria mayeri* de Loriol has been collected in the same level, in other sections.

The faunal assemblage emphasises a clear change: Cardioceratinae (22%) and Peltoceratinae (32 %) remain abundant, but Hecticoceratinae decrease (10%) while Phylloceratinae remain at around 23%, a relatively low value for the Terres Noires Fm.

Level 8B: The outstanding characteristic event during this interval (Bonnot & Cariou, 1999) is the replacement of *Peltoceratoides eugenii* (Raspail) by *Peltoceratoides athletoides* (Lahusen). *Brightia thuouxensis* Fortwengler & Marchand has disappeared; only *Brightia chatillonense* de Loriol remains.

The "advanced" morphology of *Cardioceras paucicostatum* Lange is still present but limited to a few specimens, while many *Scarburgiceras scarburgense* Young & Bird are also found. Some Cardioceratinae have strong wide-set ribbing, and those specimens with thicker whorls tend towards *Cardioceras mariae* (d'Orbigny). *Taramelliceras episcopalis* de Loriol, *Lissoceras erato* (d'Orbigny) and *Lytoceras fimbriatum* Sowerby are more frequent.

The ammonite faunal assemblages continue to evolve: Cardioceratinae and Hecticoceratinae become much rarer (around 4%); *Peltoceratoides* are still abundant (17%) in Level 8B; the great abundance of Phylloceratinae (52%), observed for the first time since the Upper Callovian Henrici Subzone, is consistent with the Terres Noires Fm palaeoenvironmental context.

Level 9: Few, poorly diversified cephalopods have been found here. The ammonite faunal assemblage is composed of Phylloceratinae (70%), mainly *Sowerbyceras tortisulcatum* d'Orbigny and *Holcophylloceras mediterraneum* (Neumayr). *Eochetoceras villersensis* (d'Orbigny) and several non-characteristic Perisphinctinae are found at the top of the level.

In other Terres Noires sections, slightly richer in ammonites, several Cardioceratinae have also been found at the top of Level 9, still close in morphology to *Cardioceras (Scarburgiceras) scarburgense* (Young & Bird) or *Quenstedtoceras (Quenstedtoceras) mariae* (d'Orbigny). A few specimens have more prorsiradiate ribbing, tending towards *Cardioceras (Scarburgiceras) woodhamense* Arkell, a species characteristic of Level 10A.

- Mariae Zone, Scarburgense Subzone, *woodhamense* Biohorizon (Fortwengler & Marchand, 1991, 1994; uppermost part of Level 9 *in* Fortwengler, 1989; Level 10A *in* Fortwengler et *al.*, 2012).

Level 10A: The base (Level 10A1) contains a more abundant and diversified ammonite fauna. Perisphinctinae, already quite well represented at the top of Level 9, become far more abundant (40%) with *Properisphinctes bernensis* de Loriol, *"Perisphinctes" picteti* de Loriol and *Perisphinctes noetlingi* de Loriol.

Only one badly preserved *Cardioceras* has been found, with dense, clearly prorsiradiate ribs, evoking *Cardioceras woodhamense* Young & Bird.

For the first time in the Terres Noires Fm, *Lissoceras* is quite abundant (10%), while Oppeliidae reappear (5%), with *Campylites socium* Haas. The subgenus *Brightia* is still found, with *Hecticoceras (Brightia) chatillonense* de Loriol, *Hecticoceras (Brightia) socini* Noetling and *Eochetoceras hersilia* (d'Orbigny). The remaining fauna includes *Taramelliceras cf. richei* de Loriol and *Lytoceras sp*. Phylloceratinae decrease markedly (38%).

Phylloceratinae are found in the middle part (Level 10A2), which is composed of several metres of marly layers (middle of the *woodhamense* Biohorizon).

At the top (Level 10A3) several large Perisphinctinae have been found in aligned calcareous nodules, with several other fragmented, badly preserved ammonites, including *Properisphinctes bernensis* de Loriol, *Perisphinctes ledonicum* de Loriol and *Taramelliceras episcopalis* de Loriol.

Dinoflagellates-Palynomorphs

Palynological investigations on the Thuoux section are currently in progress. The preliminary results show the good quality of preservation and the very high richness of the organic residue (Fig. 23). The slides contain abundant dark charcoal particles, but also spores and pollen, acritarchs, rare foraminifer linings and numerous dinoflagellate cysts.

Because of their rapid evolution and diversification at the Dogger-Malm boundary, dinoflagellate cysts are an interesting biostratigraphic tool, while all other palynomorphs show no significant evolution during the same stratigraphic interval. The focus of this palynological study will therefore be the distribution of dinoflagellate cysts in the Thuoux section.

Dinoflagellate cyst assemblages in Thuoux follow the global trend described elsewhere in Europe, i.e. increasing diversity during the Late Callovian. The assemblages observed in the Thuoux section include common taxa such as *Adnatosphaeridium caulleryi*, *Compositosphaeridium polonicum*, *Gonyaulacysta jurassica*, *Impletosphaeridium spp.*, *Pareodinia ceratophora*, *Sentusidinium rioultii*, *Stephanelytron spp.* and *Tubotuberella spp*. Also present are *Energlynia acollaris*, *Rhynchodiniopsis cladophora*, *Sirmiodiniopsis orbis*, *Scriniodinium crystallinum*, *Trichodinium scarburghensis*, *Liesbergia liesbergensis*, *Rigaudella aemula*, *Wanaea fimbriata* and *Wanaea thysanota*.

Figure 22 shows the stratigraphic range of a selection of taxa, of biostratigraphic interest, used to describe the Dogger-Malm boundary in three European areas (Feist-Burkhardt & Wille, 1992; Riding & Thomas, 1992; Huault, 1999). Despite some discrepancies, this table clearly demonstrates the value of the FAD of *Wanaea fimbriata* and *Gonyaulacysta jurassica jurassica* for the characterisation of the Dogger-Malm boundary.

The richness of the samples in the Thuoux section and their good correlation with ammonite biozones could be of major interest to resolve some of the discrepancies mentioned above.

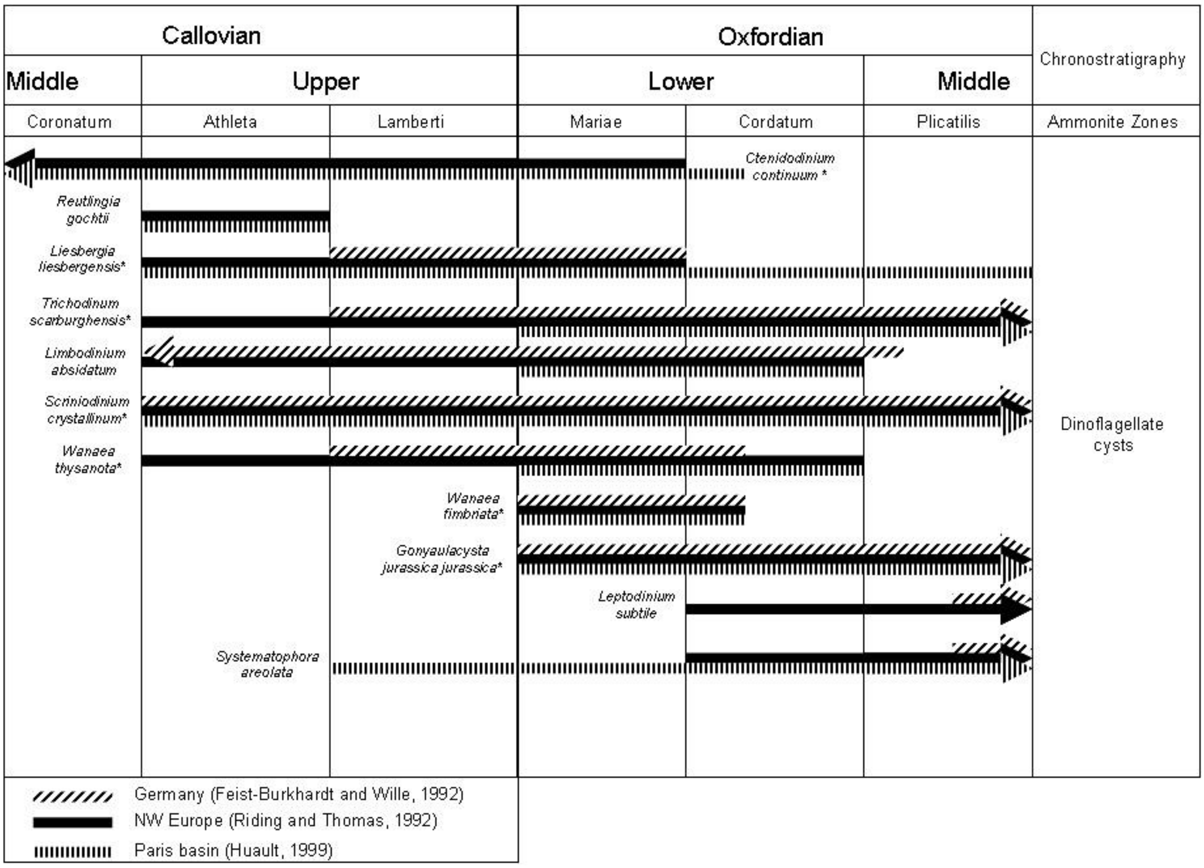
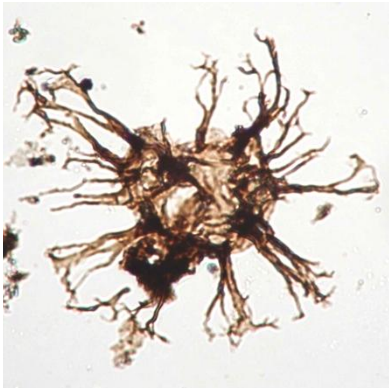
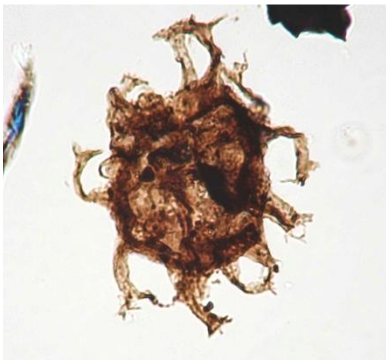


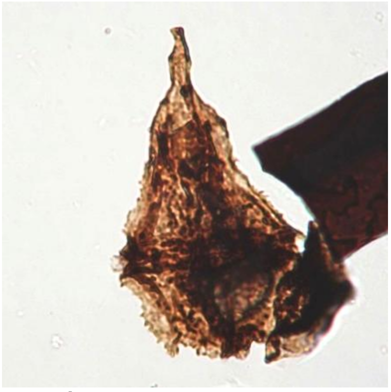
Figure 22: Comparison between the distributions of the main dinoflagellate cysts used to characterise the Dogger-Malm boundary in NW Europe (Riding et Thomas, 1992), France (Huault, 1999) and Germany (Feist-Burkhardt & Wille, 1992). Asterisks (*) indicate the dinoflagellate cysts recognised in the Thuoux section.



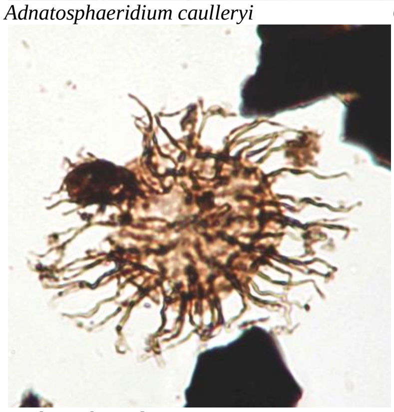
Adnatosphaeridium caulleryi



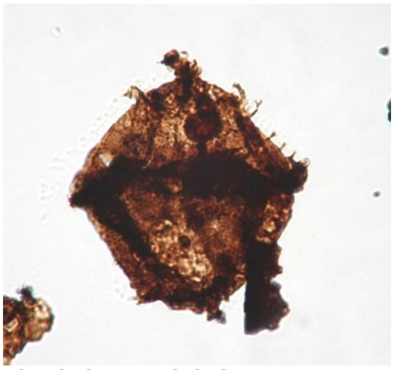
Compositosphaeridium polonicum



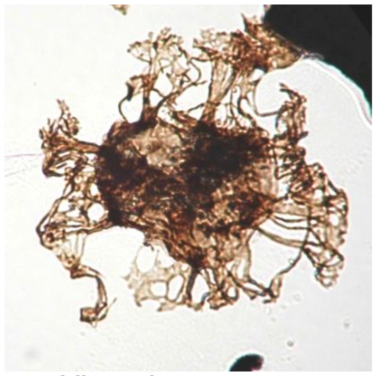
Gonyaulacysta jurassica jurassica



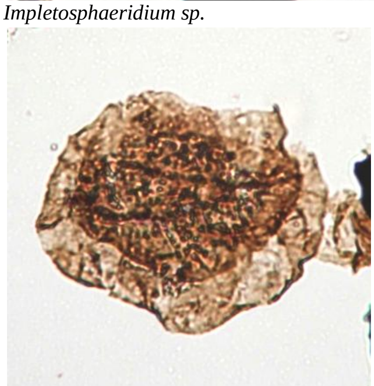
Impletosphaeridium sp.



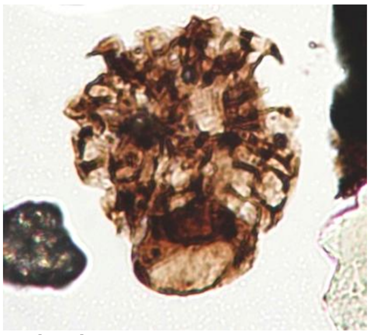
Rhynchodiniopsis cladophora



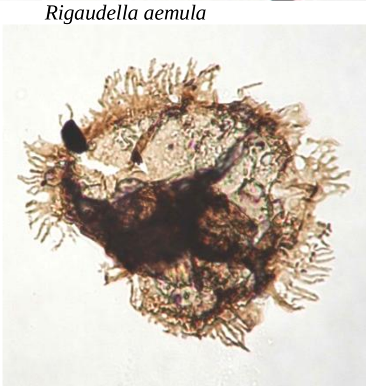
Rigaudella aemula



Sirmiodiniopsis orbis



Stephanelytron caytonense



Wanaea thysanota

Figure 23: Dinoflagellate cysts from the Thuoux section. The scale is the same for all pictures (overall size about 50 µm, except for Impletosphaeridium sp., about 40 µm, and Stephanelytron caytonense, 35 µm).

Chemostratigraphy

Bulk-carbonate $\delta^{13}C$ ($\delta^{13}C_{carb}$) data obtained on marls from the Thuoux section show marked fluctuations, with minimum values from around 0 ‰ to maximum values close to 2 ‰. Although the values are quite scattered in some intervals, significant trends across the MLJ (Middle-Late Jurassic) boundary are still clearly discernible (Fig. 24, 25). In the lower part (uppermost part of the Lamberti Subzone and lower part of the Paucicostatum Subzone), $\delta^{13}C_{carb}$ is characterised by low values (interval a) and two pronounced negative spikes (b and d). In the upper part of the Paucicostatum Subzone (interval e-f), the values gradually increase to maximum values (2 ‰) close to the MLJ boundary and remain relatively high over a large part of the *thuouxensis* Biohorizon and the lower part of the Scarburgense Subzone, interrupted by a negative spike (g-h) in the uppermost part of the *thuouxensis* Biohorizon. In the upper part of the curve (interval m-n) the $\delta^{13}C_{carb}$ values decrease again. This general pattern of the $\delta^{13}C_{carb}$ curve does not correlate with carbonate content and oxygen-isotope values, and therefore mirrors at least in part the primary environmental signal (Fig. 24). The ~ 1,5 ‰ increasing $\delta^{13}C_{carb}$ trend around the Callovian-Oxfordian boundary and the lowermost Oxfordian has already been documented in other sections and boreholes in France, Switzerland and elsewhere (e. g. Tremolada et al. 2006; Louis-Schmid et al. 2007; Pellenard et al., 2013b, Fig. 25). The isolated outlier negative $\delta^{13}C_{carb}$ values correlated with low $\delta^{18}O$ values are probably due to diagenetic alteration. Some short-lived negative $\delta^{13}C_{carb}$ values correspond to minor variations in $\delta^{18}O$. This peculiar pattern could indicate ^{13}C-depleted carbonate precipitation as the result of the microbial anaerobic oxidation of methane and sulphate reduction (relatively high $\delta^{18}O$ values), occurring within a few centimetres of the seafloor in a hydrocarbon seep environment (Louis-Schmid et al. 2007). In this case, these negative $\delta^{13}C_{carb}$ spikes could have a local cause. Further analyses are needed (*e.g.* $\delta^{13}C_{org}$) to better understand the local or global nature of these negative $\delta^{13}C_{carb}$ spikes.

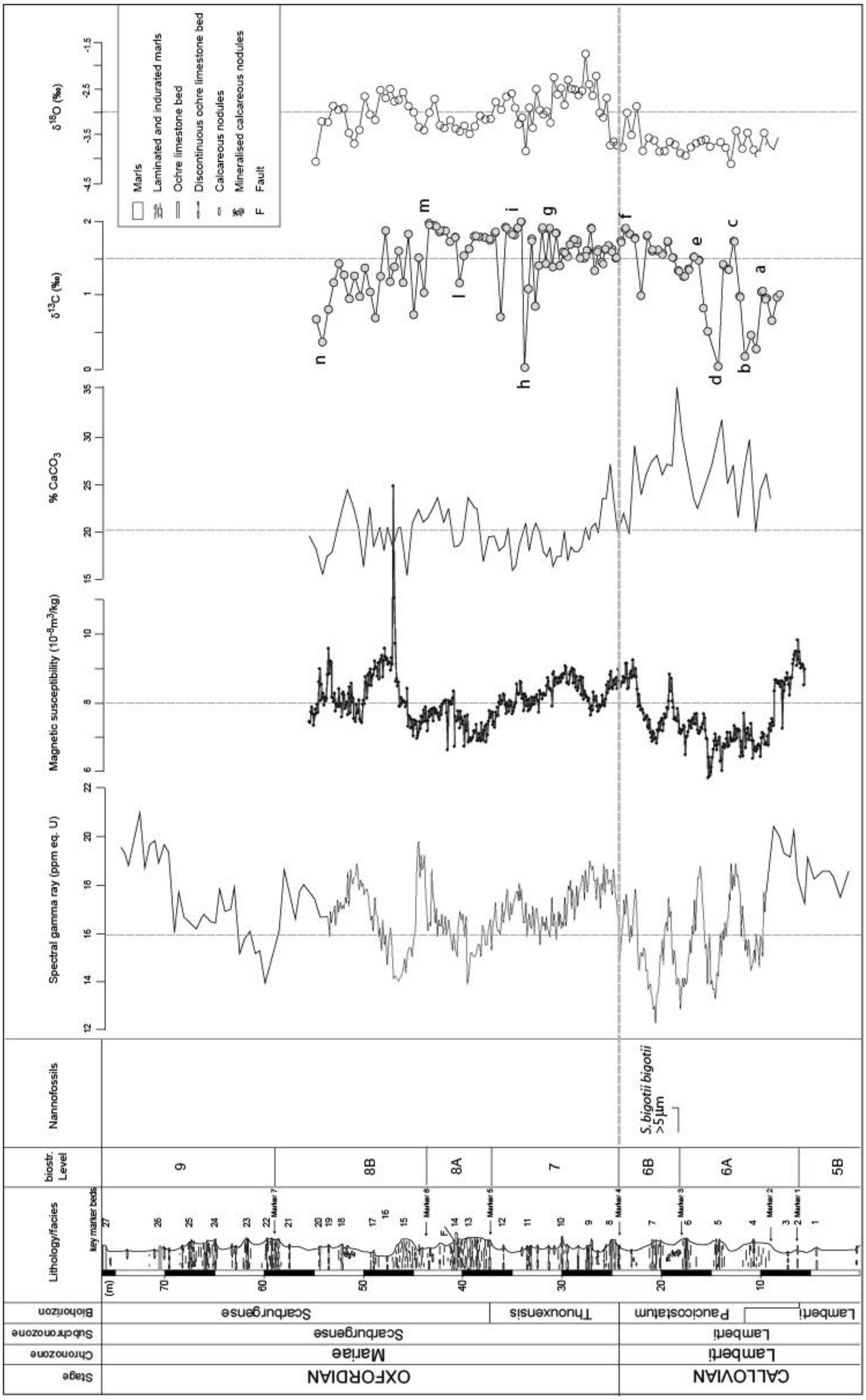


Figure 24: Physical stratigraphy and chemostratigraphy of the Thuoux section.

Physical stratigraphy (magnetic susceptibility and gamma-ray spectrometry)

In the Thuoux section, we sampled about 45 m of an interval spanning the Callovian-Oxfordian boundary (Lamberti *p.p.* and Scarburgense Subzones *p.p.*, Fig. 24). The sampling step was fixed at ~8 cm, resulting in 570 samples. The 570 samples collected were measured for magnetic susceptibility (MS) with a Kappabridge susceptometer MFK-1. Each sample was measured three times, and the mean of these values is reported after weight normalisation. The standard deviation of the analytical error associated with the MS measurements, based on triplicate analyses, is $0.0091\text{x}10^{-8}$ m^3/kg.

The MS values are relatively low (ranging from 6 to $10\text{x}10^{-8}$ m^3/kg) and their variations follow a strongly cyclical pattern (Fig. 23). There are short-wavelength cycles superimposed on a long-wavelength cycle, which reaches its maximum ($10\text{x}10^{-8}$ m^3/kg) around the Callovian-Oxfordian boundary. Visual inspection indicates a mean wavelength of ~6.5 m for the high-frequency oscillations. Such cyclical variations in the MS signal will be studied in detail.

A total of 1730 field gamma-ray spectrometry measurements (GRS) were collected with a sampling step of precisely 50 cm across the Callovian-Oxfordian boundary, at Condorcet, Montréal-les-Sources, Savournon, Thuoux, Aspres-sur-Büech and St Pierre d'Argençon, for accurate correlation throughout the Subalpine Basin, in relation to biostratigraphy (Fig.10). High-resolution investigations were performed at Thuoux, from Level 6A to Level 8B, with a sampling step of precisely 12 cm (280 data-points, Figs. 21, 24). Field spectral gamma-ray data were collected, using both a field spectrometer Exploranium GR-320, and a SatisGeo GS-512 equipped with a ^{137}Cs reference source. A consistent methodology was applied: the detector was placed against a cleaned and smoothed outcrop surface, with an acquisition time of 1 min. Reproducibility was assessed by measuring the same spot 30 times. Replicates are normally distributed (Shapiro-Wilk test: $p>0.05$), with a standard deviation of approximately 5%, confirming the validity of a 1-min acquisition time. Data range from 12 to 22 ppm eq.U, which is common for marl values. Well-expressed cyclical fluctuations are observed at Thuoux, especially for the Upper Callovian, which generally match the magnetic susceptibility signal with an inverse relationship to carbonate-rich deposits, proving that high values are linked to a high concentration in clay minerals. Preliminary statistical analyses, such as multitaper spectral analysis, show that sedimentary cycles are orbitally driven, as previously demonstrated for Thuoux and Saint Pierre d'Argençon with a sampling step of 50 cm (Gaspard 2005; Huret 2006; Pellenard et al., *in progress*).

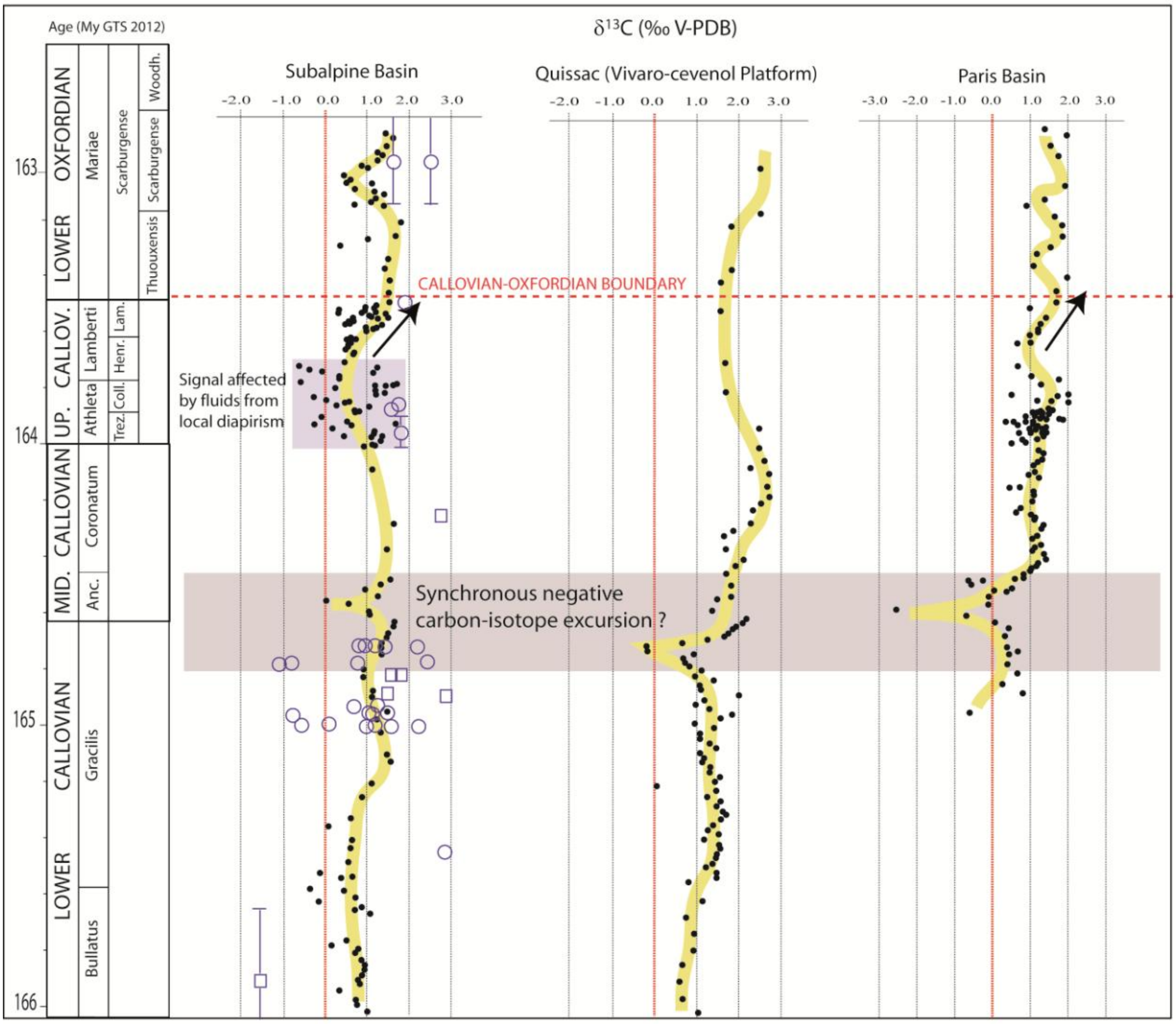


Figure 25: Carbon-isotope chemostratigraphy from bulk data of the Subalpine Basin during the Lower Callovian-Lower Oxfordian interval (composite section using data from La Voulte-sur-Rhone, Propriac-Beauvoisin and Thuoux, Cornuault, 2013, unpublished data). Comparison with the Quissac section from the Vivaro-Cevenol Platform (Bartolini, unpublished data) and the Paris Basin (Pellenard et al., 2013b). An increasing trend in the $\delta^{13}C$ curve is observed close to the Callovian-Oxfordian boundary, from the end of the Athleta Zone, providing a key marker for the stage boundary. Taking into account the biostratigraphic uncertainties at the Lower Callovian-Middle Callovian, a negative excursion is probably synchronous for the three areas. Carbon-isotope data from diagenetically screened belemnites from the Subalpine Basin are reported (purple circles: Hibolites; purple squares: undetermined).

Field trip 3: The Lazer section

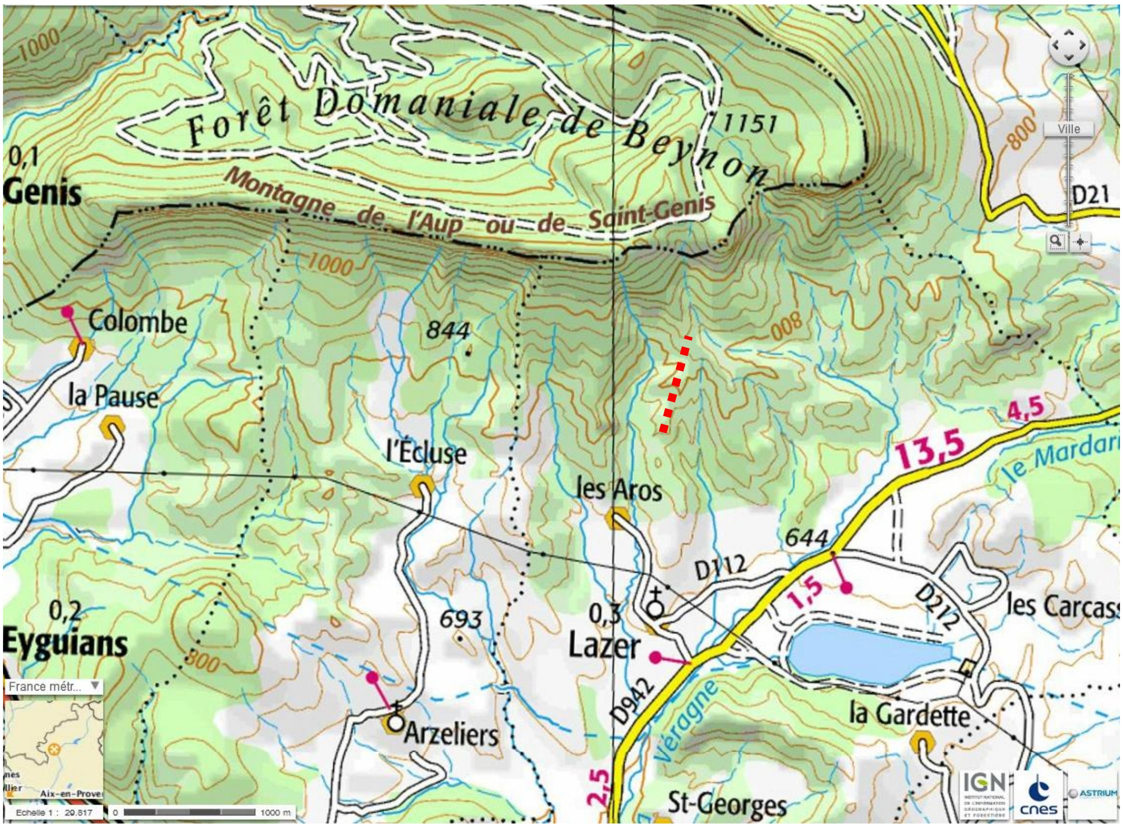


Figure 26: The Le Sarret-Serres outcrop (dashed red line)

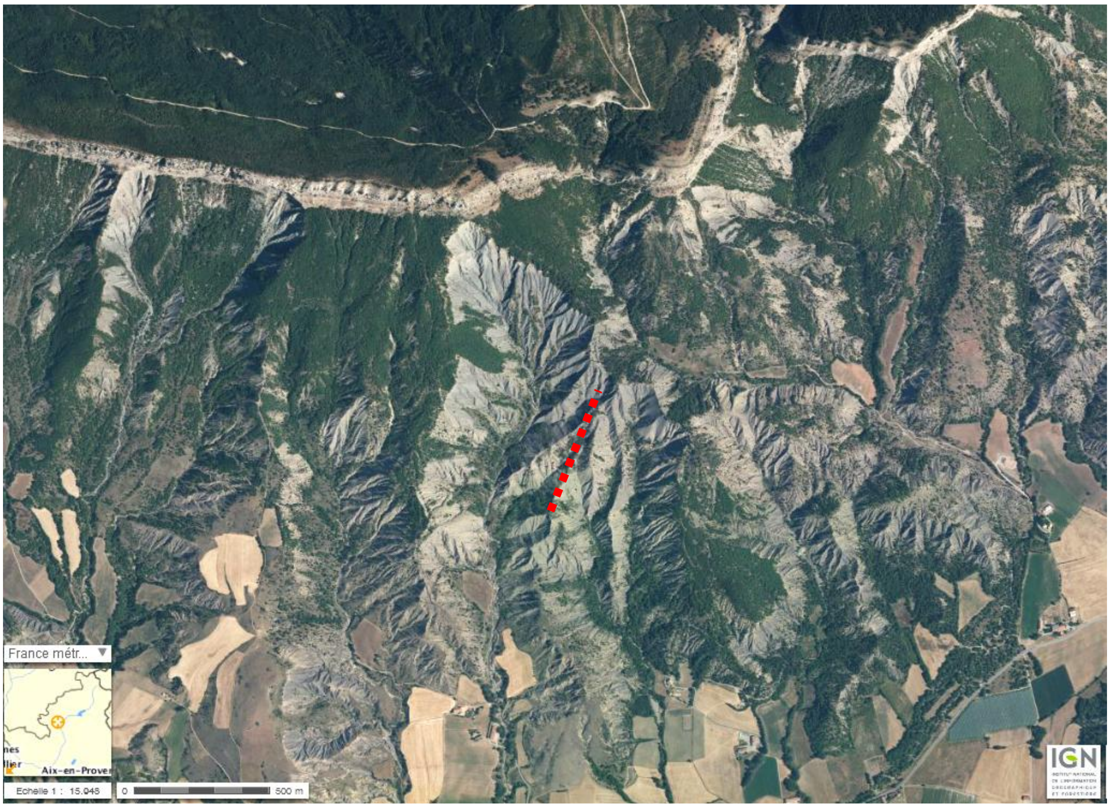


Figure 27: Aerial photograph of the Lazer section (Les Aros-St Romain, coordinates of the Callovian-Oxfordian boundary: 44°21'55"N latitude, 005°50'24"E longitude)

The Terres Noires Fm crops out very well along an extended crest, with no stratigraphic gaps from the Bathonian to the Middle Oxfordian (Argovian facies). Only the interval which encompasses the Callovian-Oxfordian boundary is described (Fig. 28), from the Lamberti Subzone, *praelamberti* Biohorizon (Upper Callovian) to the Scarburgense Subzone, *scarburgense* Biohorizon (Lower Oxfordian).

- Level 4 (5.5 m): the lowest part is composed of soft marls with numerous beds of chocolate-brown nodules. The lower part (Level 4B) contains very small nodules, while the upper part is lighter in colour, with larger nodules. The abundant ammonite fauna is mainly composed of Hecticoceratinae. Several rare *Quenstedtoceras*, found near Lazer, in the same levels, indicate Lamberti Zone, Lamberti Subzone, *praelamberti* Biohorizon.
- Levels 5A-5B (45 m): they are composed of soft marls with facies similar to Level 4 but containing larger cream- to brick-coloured nodules. The ammonites, especially the Quenstedtoceratids, are typical of the Lamberti Zone, Lamberti Subzone, *praelamberti* and *lamberti* biohorizons.
- Level 6 (25 m): marly facies similar to lower levels, with grey nodules; Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon.
- Levels 7-8A (25 m): marls become darker and harder, with several interbedded large orange-to-ochre platy nodules at the base. Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon (Level 7) and the base of the *scarburgense* Biohorizon (Level 8A).
- Levels 8B-9 (75m): thick marls with large, orange-to-ochre platy nodules, more or less aligned in Level 8B, but more randomly distributed in Level 9; the upper part of the Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon p.p.

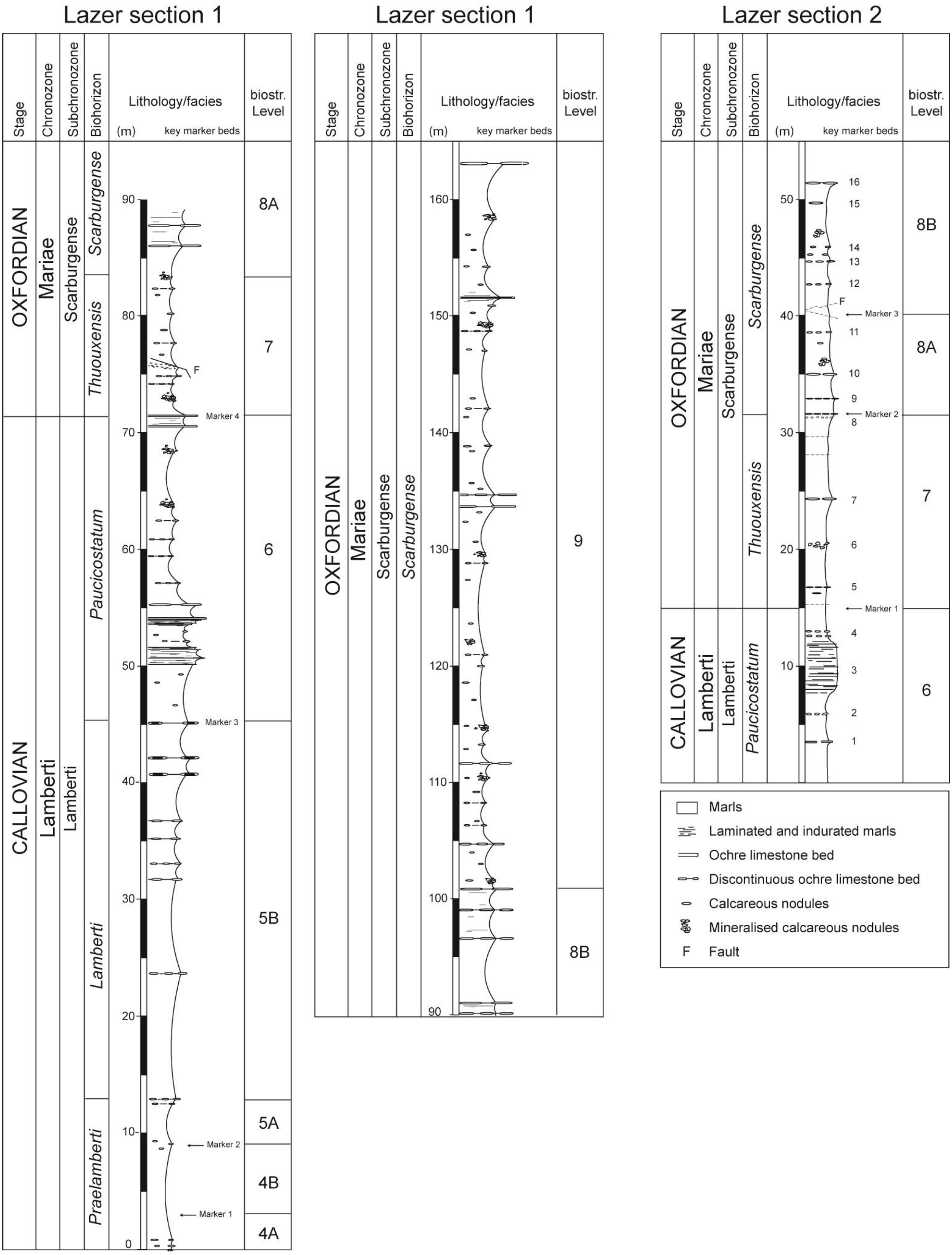


Figure 28: Biostratigraphy, lithology and facies of the Terres Noires Fm at Lazer

The fossil record

Ammonites

* UPPER CALLOVIAN

- Lamberti Zone, Lamberti Subzone, *praelamberti* Biohorizon (Marchand, 1986; Level 4 and base of Level 5 *in* Fortwengler, 1989; base of *lamberti* Biohorizon (Level 5A), *in* Fortwengler et al., 1997).

Level 4A is characterised by numerous Phylloceratinae and Hecticoceratinae, including Hecticoceras (Putealiceras) punctatum Stahl, Hecticoceras (Orbignyceras) pseudopunctatum Lahusen. The Perisphinctidae include Poculisphinctes poculum Leckenby and Alligaticeras sp. Rare Quenstedtoceras are found in nearby sections, at the same stratigraphic level, indicating a position very close to the boundary of the Henrici Subzone (*henrici* Biohorizon) and the Lamberti Subzone (*praelamberti* Biohorizon). Level 4B contains abundant Pseudoperisphinctinae. In many other sections, this level is not recognisable from ammonite fauna, attesting to the high sedimentation rate at Lazer.

Level 5A contains abundant ammonites, which are often fragmented, as in the nearby Savournon-Peyrale section. As in most of the sections studied, Poculisphinctes poculum Leckenby is quite abundant (15%), with less abundant Quenstedtoceras praelamberti Douvillé (13%) than in other sections, where they reach 40%.

- Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon (Hébert, 1857); Callomon, 1964, emend. Marchand, 1986; uppermost part of Level 5 *in* Fortwengler, 1989; Level 5B *in* Fortwengler et al., 1997).

The biohorizon is easily recognisable with the classical association of rare Quenstedtoceras lamberti Sowerby, Poculisphinctes poculum Leckenby and Alligaticeras alligatum Leckenby.

- Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon (Marchand, 1979, emend. Fortwengler & Marchand, 1994; Level 6 *in* Fortwengler, 1989 and Fortwengler et al., 1997).

The *paucicostatum* Biohorizon is thinner at Lazer and consequently cannot be subdivided. Oppeliidae are abundant, particularly Hecticoceras (Orbignyceras) paulowi (de Tsytovitch), and Cardioceratidae, with Cardioceras paucicostatum (Lange).

* LOWER OXFORDIAN

- Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon (Fortwengler et al., 1997; *elisabethae* Biohorizon *in* Fortwengler & Marchand, 1994; Level 7 *in* Fortwengler, 1989).

The Callovian-Oxfordian boundary can be better observed some ten metres to the east, because of a small fault above Level 6. Small, fragmented ammonites are abundant. In Level 7, at Lazer, as at Thuoux, Savournon and Saint-Pierre d'Argençon, Callovian ammonites of the *Poculisphinctes*, *Orbignyceras*, *Putealiceras* and *Alligaticeras* genera are no longer found. The faunal assemblage is composed of Hecticoceras (Brightia) thuouxensis Fortwengler & Marchand (39%), Cardioceras paucicostatum Lange (advanced morph) and Peltoceratoides eugenii Raspail (det. Bonnot). Phylloceratinae are even more abundant (19%) than at Savournon.

- Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon (Fortwengler & Marchand, 1991, 1994; uppermost part of Level 9 *in* Fortwengler, 1989; Level 10 A *in* Fortwengler et al., 2012).

Throughout the Subalpine Basin, the *scarburgense* Biohorizon can be divided into three levels, each characterised by typical ammonite assemblages and by the appearance of new species.

Level 8A contains abundant ammonites, including Hecticoceras (Brightia) chatillonense de Loriol, present for the first time, with Peltoceratoides eugenii Raspail, a persistent taxon. As the ammonite fossils are small (internal whorls), it is often difficult to distinguish Cardioceras paucicostatum Lange from Cardioceras (Scarburgiceras) scarburgense (Young & Bird).

In Level 8B, Peltoceratoides eugenii Raspail is replaced by Peltoceratoides athletoides Lahusen, while the Phylloceratinae become very abundant (72%).

In Level 9, Peltoceratinae and Cardioceratinae are absent but Phylloceratinae are still abundant.

Field trip 4: The Savournon section

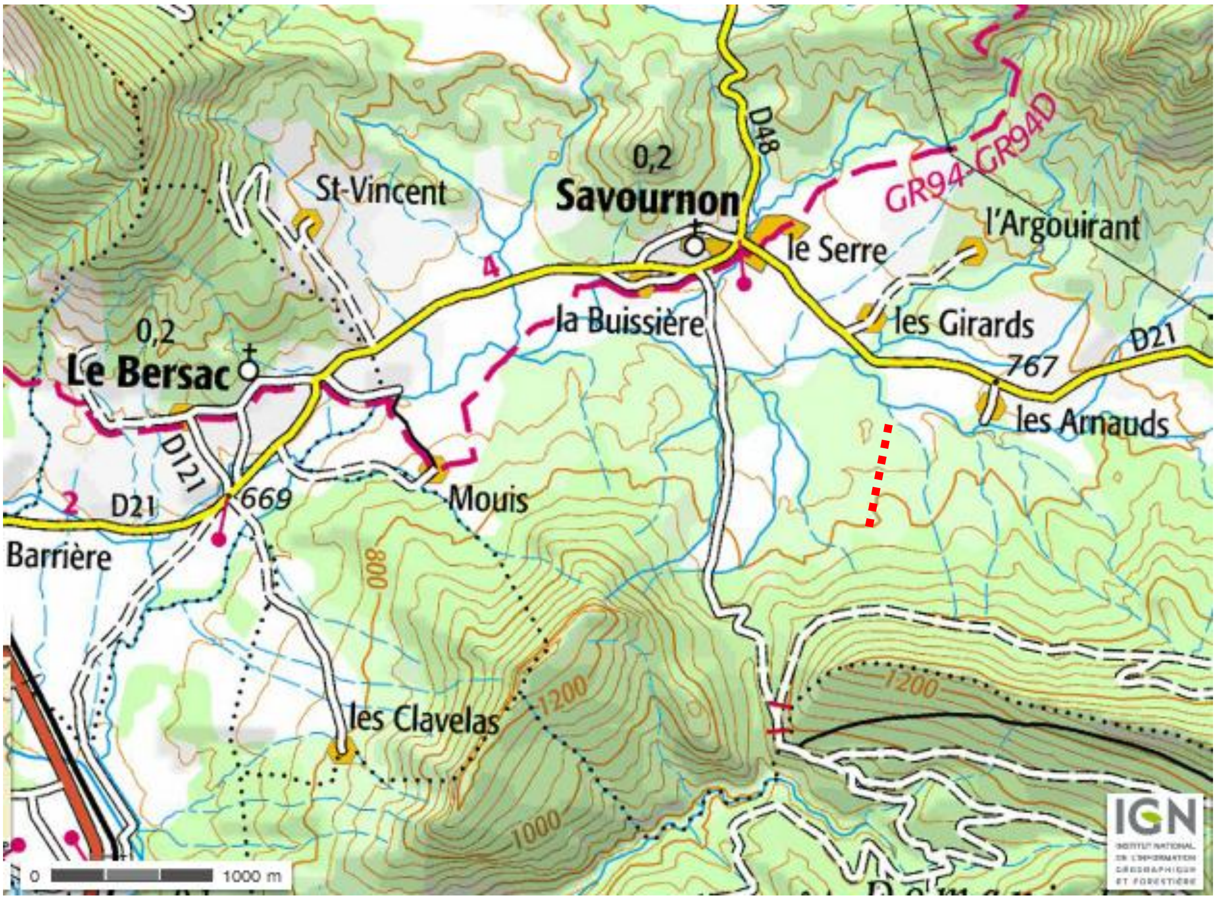


Figure 29: The Savournon-Peyrale outcrop (dashed red line)

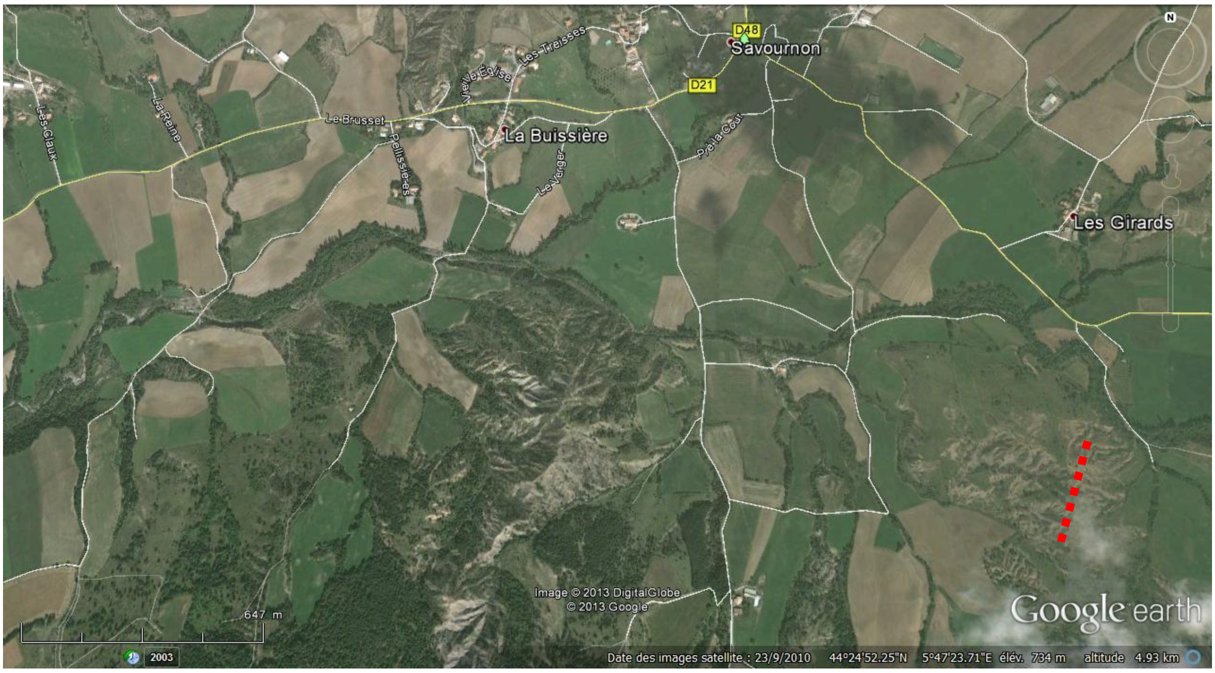


Figure 30: Aerial photograph of the Savournon-Peyrale section (coordinates of the Callovian-Oxfordian boundary: 44°24'35"N latitude, 005°48'16"E longitude)

a b c

Figure 31: Photographs of the Savournon section showing a: general view of the outcrop, b: end of the section

The presence of horizontal faults has affected this sedimentary succession, duplicating part of the Terres Noires series. This section therefore requires particular attention with regard to any observations. Only the faulted block spanning the Callovian-Oxfordian boundary is presented here, from Level 5B to Level 10A (Fig. 32; Fortwengler & Marchand, 1994c; Fortwengler *et al*., 1997; Atrops & Meléndez, 2003; Meléndez *et al*., 2007; Fortwengler *et al*., 2012).

- Level 5B: (15 m) soft grey to yellowish marls, rich in large orange-to-ochre platy nodules, which are often aligned (Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon).

- Levels 6A-6B: (20 m) very soft light grey marls, with several thin more calcareous intercalations (Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon).

- Levels 7 and 8A: (40 m) thick dark marls with abundant cream-coloured nodules with some large orange-to-ochre platy nodules (Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon and base of the *scarburgense* Biohorizon).

- Level 8B: (12 m) marls, a very similar facies to Levels 7 and 8A, but containing numerous interbedded large orange-to-ochre platy nodules (Fig. 31c) Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon *p.p.*).

- Level 9: (48 m) very thick grey marls with rare nodules and some large platy nodules (Mariae Zone, Scarburgense Subzone, uppermost part of *scarburgense* Biohorizon).

- Level 10A: only 25 m of soft marls can be observed because the upper part of this level is affected by a fault (Fig. 31b); the visible part contains numerous large orange-to-ochre platy nodules and small greenish phosphatic nodules (Mariae Zone, Scarburgense Subzone, *woodhamense* Biohorizon).

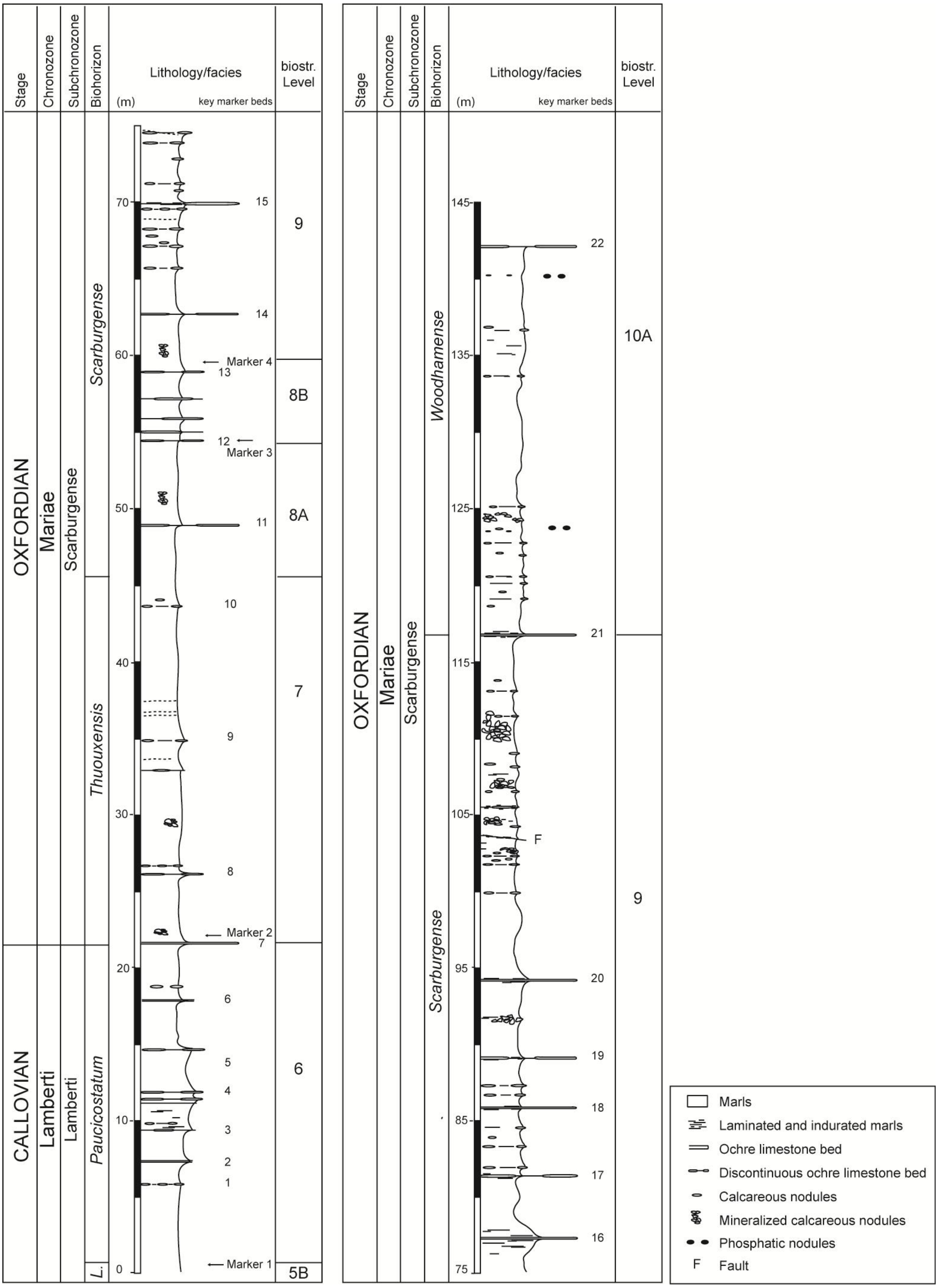


Figure 32: Biostratigraphy, lithology and facies of the Terres Noires Fm at Savournon

The fossil record

Ammonites

* UPPER CALLOVIAN

- Lamberti Zone, Lamberti Subzone, *praelamberti* Biohorizon (Marchand, 1986; base of Level 5 *in* Fortwengler, 1989; base of *lamberti* Biohorizon (Level 5A), *in* Fortwengler *et al.*, 1997).

Just below the fault duplicating the marly base of the Savournon-Peyrale section, a small outcrop contains several characteristic *Quenstedtoceras praelamberti* Douvillé.

- Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon (Hébert, 1857); *emend*. Marchand, 1986; uppermost part of Level 5 *in* Fortwengler, 1989; Level 5B *in* Fortwengler *et al.,* 1997).

At Peyrale, the large nodules in Level 5B frequently contain fragmented fossils.

As in most of the sections studied, the Pseudoperisphinctinae and Perisphinctinae are dominant (44%). The Cardioceratinae are extremely rare, while the abundance of Hecticoceratinae (13%) is between that of Thuoux (8%) and Saint-Pierre d'Argençon (20%). Phylloceratinae are significantly more abundant (29%).

- Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon (Marchand, 1979, *emend*. Fortwengler & Marchand, 1994; Level 6 *in* Fortwengler, 1989 and Fortwengler *et al.*, 1997).

The *paucicostatum* Biohorizon crops out very well at Savournon (20 m). Fossils are well preserved and often larger than at Thuoux. It is difficult to define a precise boundary between Levels 6A and 6B because of the topography.

The faunal assemblage is similar to that at Thuoux. Cardioceratinae are less abundant (8% *versus* 18%), but Perisphinctidae are more abundant. Among the Oppellidae, *Orbignyceras paulowi* de Tsytovich is dominant. *Hecticoceras coelatum* Coquand has also been found, but is extremely rare.

* LOWER OXFORDIAN

- Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon (Fortwengler *et al.*, 1997; *elisabethae* Biohorizon *in* Fortwengler & Marchand, 1994; Level 7 *in* Fortwengler, 1989).

<u>Level 7</u>: (9m) thinner here than at Thuoux (13m). The marly deposits are intercalated

with thin layers of small nodules, containing abundant calcareous ammonites, often poorly preserved due to weathering.

Just after the last appearance datum of the Callovian species Hecticoceratinae and Pseudoperisphinctinae, as at Thuoux and Saint-Pierre d'Argençon, a faunal renewal is observed. *Hecticoceras (Brightia) thuouxensis* is very abundant (30%). The remaining fauna is the same as at Thuoux and Saint-Pierre d'Argençon. The faunal assemblage is very similar to that at Thuoux, but with more abundant Phylloceratidae (20%).

Levels 8A and 8B: As in Level 7, the base of the *scarburgense* Biohorizon crops out very well. Levels 8A and 8B can be recognised by three criteria: the first appearance datum of *Brightia chatillonense* de Loriol in Level 8A; the first appearance datum of *Peltoceratoides athletoides* (Lahusen) in Level 8B; moderately abundant Phylloceratinae in Level 8A, becoming dominant in Level 8B.

The faunal assemblage in Level 8A is slightly different from that at Thuoux, with more abundant Phylloceratinae and rarer Cardioceratinae. The faunal assemblage in Level 8B more closely resembles that at Thuoux.

Level 9: Relatively thin at Savournon, with rare ammonites, far lower species diversity and marked dominance of Phylloceratinae.

- Mariae Zone, Scarburgense Subzone, *woodhamense* Biohorizon (Fortwengler & Marchand, 1991, 1994; uppermost part of Level 9 *in* Fortwengler, 1989; Level 10 A *in* Fortwengler *et al.*, 2012).

Level 10A: Outcrops contain abundant ammonites, which are often badly preserved, and fragmented by intense weathering. As at the Thuoux and Saint-Pierre d'Argençon sections, this level can be divided into three parts, based on ammonite species diversity.

In Level 10A1, the fauna is very similar to that found at Thuoux, and the Phylloceratinae are even more dominant (48%, compared to 38% at Thuoux) but the Perisphinctinae are less abundant (27 % compared to 40 % at Thuoux).

Level 10A2 is very rich in Phylloceratinae (70%), while in Level 10A3 the ammonite record increases in diversity. The Perisphinctinae reach 32%, while the Oppeliidae decrease to around 10%, as in Level 10A1. For the first time, *Brightia bonarellii* de Loriol and *Brightia kautzschi* Noetling are present.

About 10 Cardioceratinae have been found among the ammonite fauna in Level 10A3. A detailed study of this small population indicates that the level is at the top of the *woodhamense* Biohorizon, as it contains specimens which already possess fine, dense ribbing, with a slight ventral keel (cf. *Cardioceras normandiana* Spath), and others with coarse ribs crossing the ventral keel, forming beaded chevrons (*Cardioceras woodhamense* Arkell). An identical population has been collected in the Boulonnais (Uzelot section, bed 50; Vidier *et al.*, 1993).

Palynology

The palynological analysis of the Savournon section was carried out by Courtinat (Courtinat, 2006). This work showed that the Callovian-Oxfordian boundary in this part of the Subalpine Basin could be defined using the usual index species *Wanaea fimbriata*, which appeared at the very beginning of the first ammonite zone (Mariae Zone) of the Oxfordian, in western Europe (Feist-Burkhardt and Wille, 1992; Riding and Thomas, 1992; Huault, 1998). Courtinat (2006) also used an endemic taxon (*Stephanelytron ceto*) to enhance the definition of this boundary. Unfortunately, this interesting study contains no illustrations of dinoflagellate cysts from the Savournon section.

Chemostratigraphy

Bulk-carbonate $\delta^{13}C$ ($\delta^{13}C_{carb}$) data on marls from the Savournon section show less marked fluctuations than in the Thuoux section, with minimum values around 1 ‰ to maximum values close to 2 ‰ (Fig. 33). Despite this, some similar trends can be highlighted: in the lower part of the Paucicostatum Subzone, $\delta^{13}C$ values are low and tend to increase across the MLJ boundary. This tendency is interrupted at the very base of the Scarburgense Zone (in the *thuouxensis* Biohorizon) by an abrupt negative shift (h). The general pattern of the curve shows a multi-spike positive excursion in the lowermost Oxfordian.

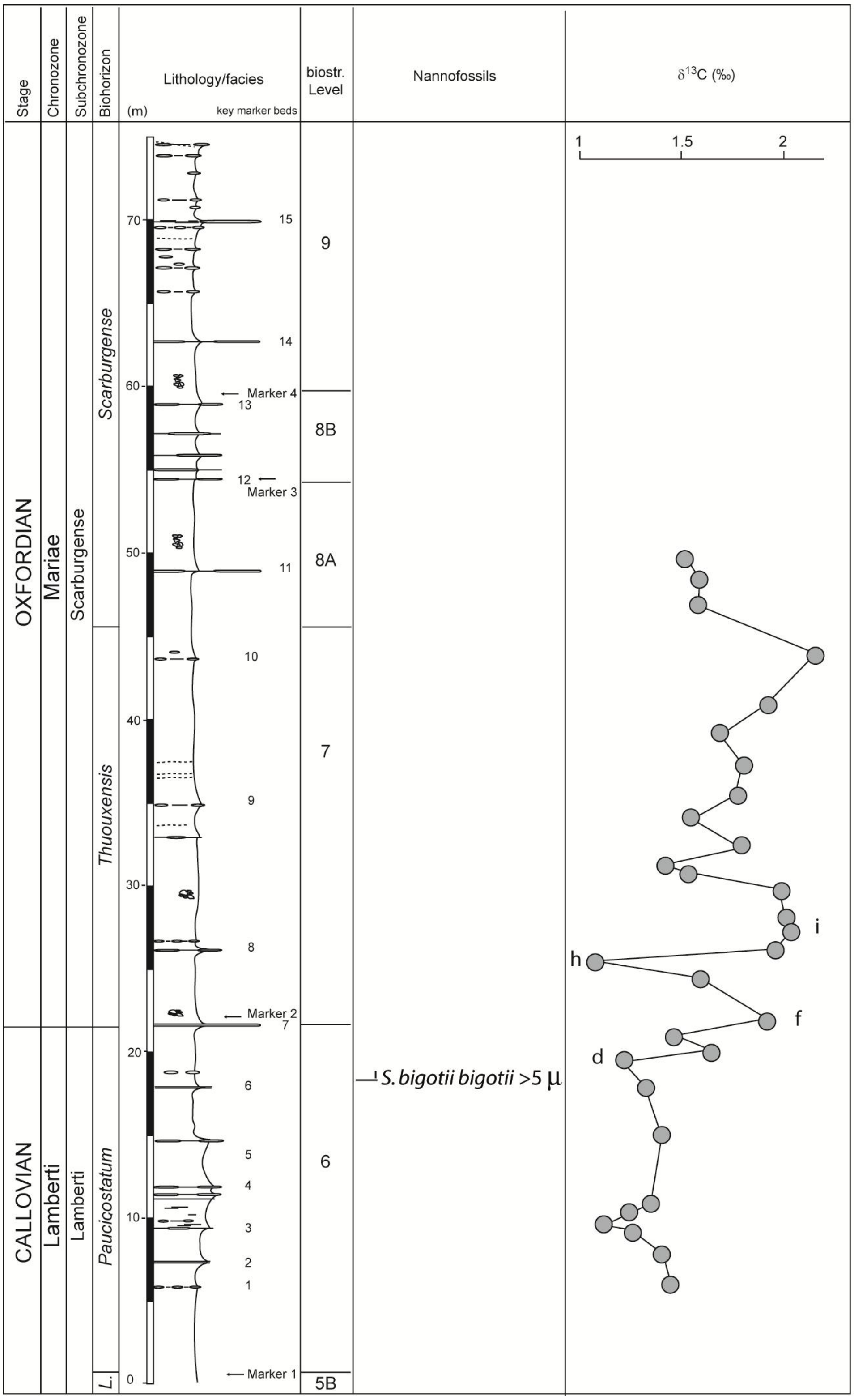


Figure 33: Nannofossil biostratigraphy and chemostratigraphy at Savournon close to the Callovian-Oxfordian boundary.

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Appendices

Ammonites

Article by Boulila et al., 2010 (Basin Research)

PLATE 1

1. *Alligaticeras aff.* alligatum LECKENBY (M). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n° DF 1741: Thuoux.

2. *Poculisphinctes poculum* LECKENBY (M). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n° DF 4588: Thuoux.

3. *Quenstedtoceras lamberti* (SOWERBY) (M). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n° DF 2584: Thuoux.

4. *Kosmoceras duncani* (SOWERBY) *in* Badaluta 1976 (fig. 6-2) (M). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n° DF 18698: Thuoux.

5. *Hecticoceras* (*Orbignyceras*) *paulowi* (de TSYTOVITCH) (M). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n° DF 2467: Thuoux.

6. *Hecticoceras (Putealiceras) punctatum* LAHUSEN (m). Level 6A, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n° DF 1376: Thuoux.

7. *Hecticoceras (Putealiceras) punctatum* LAHUSEN (M). Level 6A, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n° DF 2503: Thuoux.

8. *Cardioceras paucicostatum* LANGE (M ?). Level 6A, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n° DF 2469: Thuoux.

9. *Hecticoceras (Lunuloceras) pseudopunctatum* (LAHUSEN) (M ?). Level 6A, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n° DF 2482: Thuoux.

10. *Poculisphinctes sp. aff. poculum* LECKENBY (m). Level 6A, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n° DF 18082: Thuoux.

11. *Hecticoceras (Lunuloceras) pseudopunctatum* LAHUSEN (m). Level 6B, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n° DF 2558: Thuoux.

12. *Cardioceras aff. paucicostatum* LANGE (m ?). Level 6B, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n° DF 2530, Thuoux.

13. *Peltoceratoides eugenii* (RASPAIL) (m). Level 6B, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n° DF 18098, Thuoux.

14. *Peltoceratoides eugenii* (RASPAIL) (M). Level 6B, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n° DF 2573: Thuoux.

Specimens are from the collection of D. Fortwengler (photographs by D. Fortwengler and plates by Simone Dutour). Scale x 1. Red dot: end of phragmocone.


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PLATE 2

1. *Peltoceras aff. schroederi* PRIESER (M). Level 6A, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n° DF 2655: Thuoux.

2. *Cardioceras (Scarburgiceras) aff. paucicostatum* Lange (M). Level 7, Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon, n° DF 1365: Thuoux.

3. *Hecticoceras (Brightia) thuouxensis* FORTWENGLER & MARCHAND (m). Level 7, Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon, n°DF 2605: Thuoux.

4. *Hecticoceras (Brightia) thuouxensis* FORTWENGLER & MARCHAND (M). Level 7, Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon, n° DF 2311: Thuoux.

5. *Hecticoceras (Brightia) thuouxensis* FORTWENGLER & MARCHAND (m). Internal whorls. Level 7, Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon, n°DF 18156: Thuoux.

6. *Euaspidoceras armatum* (de LORIOL). Level 7, Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon, n°DF 1457: Thuoux.

7 a, b. *Peltoceratoides eugenii* (RASPAIL) morph *eugenii* RASPAIL (M). Level 7, Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon, n° DF 1666: Thuoux.

8 a, b, c. *Peltoceras eugenii* (RAISPAIL) morph *eugenii* RASPAIL (M). Level 7, Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon, n°DF 2655: Thuoux.

9 a, b, c. *Hecticoceras coelatum* (COQUAND). Level 8A, Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon, n°DF 1617: Thuoux.

10. *Cardioceras aff. scarburgense* YOUNG & BIRD. Level 8A, base of the Mariae Zone, Scarburgense Subzone, *scarburgense* Biohorizon, n°DF 18751: Thuoux.

11. *Cardioceras aff. scarburgense* YOUNG & BIRD. Level 8A, base of the Mariae Zone,

Scarburgense Subzone, *scarburgense* Biohorizon, n° DF 18752: Thuoux.

Specimens are from the collection of D. Fortwengler (photographs by D. Fortwengler and plates by Simone Dutour). Scale x 1. Red dot: end of phragmocone.


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PLATE 3

1 a,b. *Cardioceras aff. paucicostatum* LANGE (M). Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 3880: Thuoux.

2. *Cardioceras aff. paucicostatum* LANGE (m). Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 3883: Thuoux.

3 a, b. *Cardioceras aff. Paucicostatum* LANGE (M). Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 3881: Thuoux.

4. *Hecticoceras (Brightia) sp* (m). Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 1608: Thuoux.

5. *Cardioceras scarburgense* YOUNG & BIRD. Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 18419: Thuoux.

6. *Hecticoceras (Brightia) thuouxensis* FORTWENGLER & MARCHAND (m). Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 18493: Thuoux.

7. *Hecticoceras (Brightia) chatillonense* de LORIOL (M). Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n° DF 18767: Thuoux

8. *Peltoceratoides eugenii* (RASPAIL) morph *eugenii* RASPAIL (M). Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 3717: Thuoux.

9. *Peltoceratoides athletoides* (LAHUSEN) morph *athletoides* LAHUSEN (M). Level 8B, Mariae Zone, Scarburgense Subzone, middle of the *scarburgense* Biohorizon, n°DF 1944: Thuoux.

10. *Peltoceratoides athletoides* (LAHUSEN) morph *athletoides* LAHUSEN (M). Level 8B, Mariae Zone, Scarburgense Subzone, middle of the *scarburgense* Biohorizon, n°DF 18563: Thuoux.

11. *Hecticoceras (Brightia) chatillonense* de LORIOL (M). Level 8B, Mariae Zone, Scarburgense Subzone, middle of the *scarburgense* Biohorizon, n°DF 1875: Thuoux.

12. *Eochetoceras villersensis* d'ORBIGNY (M). Level 8B, Mariae Zone, Scarburgense Subzone, middle of the *scarburgense* Biohorizon, n° DF 1385: Thuoux.

13. *Cardioceras scarburgense* YOUNG & BIRD. Level 8B, Mariae Zone, Scarburgense Subzone, middle of the *scarburgense* Biohorizon, n° DF 1659: Thuoux.

14 a, b. *Taramelliceras episcopalis* (de LORIOL). Level 8B, Mariae Zone, Scarburgense Subzone, middle of the *scarburgense* Biohorizon, n°DF 19536: Thuoux.

15. *Poculisphinctes sp.* (m). Level 4, Lamberti Zone, Henrici Subzone, n°DF 581: Saint-Pierre d'Argençon.

16. *Quenstedtoceras praelamberti* DOUVILLE (M). Level 5A, Lamberti Zone, Lamberti Subzone, *praelamberti* Biohorizon, n°DF 14517: Saint Pierre d'Argençon.

17. *Hecticoceras (Lunuloceras) pseudopunctatum* LAHUSEN *in* de LORIOL 1914 (Pl.II Fig. 2). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n° DF 586: Saint-Pierre d'Argençon.

18 a, b. *Distichoceras bipartitum* (ZIETEN). Level 5B, Lamberti Zone, Lamberti Subzone, n° DF 2703: Saint-Pierre d'Argençon.

19. *Poculisphinctes poculum* LECKENBY (M). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n° DF 2727: Saint Pierre d'Argençon.

Specimens are from the collection of D. Fortwengler (photographs by D. Fortwengler and plates by Simone Dutour). Scale x 1. Red dot: end of phragmocone.


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PLATE 4

1. *Hecticoceras (Orbignyceras) paulowi* (de TSYTOVICH) (M). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n°DF 2719: Saint-Pierre d'Argençon.

2. *Alligaticeras aff. alligatum* LECKENBY (M). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n°DF 14518: Saint-Pierre d'Argençon.

3 a, b. *Euaspidoceras subbabeanum* (SINTZOV), morph *subbabeanum* SINTZOV (M). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n°DF 2734: Saint-Pierre d'Argençon.

4. *Hecticoceras (Lunuloceras) pseudopunctatum* (LAHUSEN) (M). Level 5B, Lamberti Zone, Lamberti Subzone, *lamberti* Biohorizon, n° DF 19527: St Pierre d'Argençon.

5. *Cardioceras paucicostatum* LANGE. Level 6, Lamberti Zone, Lamberti Subzone, *paucicostatum* Biohorizon, n°DF 4063: Saint-Pierre d'Argençon.

6. *Cardioceras (Scarburgiceras) aff. paucicostatum* LANGE. Level 7, Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon, n°DF 2814: St Pierre d'Argençon.

7. *Hecticoceras (Brightia) thuouxensis* FORTWENGLER & MARCHAND (m). Level 7, Mariae Zone, Scarburgense Subzone, *thuouxensis* Biohorizon, n° DF 19532: Saint-Pierre d'Argençon.

8. *Cardioceras scarburgense* YOUNG & BIRD. Base of Level 8A. Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 4076: St Pierre d'Argençon**.**

9. *Hecticoceras* (*Brightia) chatillonense* de LORIOL (M). Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 19533, St Pierre d'Argençon.

10. *Peltoceratoides eugenii* (RASPAIL) (m). Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 19537: Saint-Pierre d'Argençon.

11. *Peltoceratoides eugenii* (RASPAIL) morph *eugenii* Raspail (M). Level 8A, Mariae Zone, Scarburgense Subzone, base of the *scarburgense* Biohorizon, n°DF 19528: Saint-Pierre d'Argençon.

12. *Cardioceras aff. paucicostatum* LANGE, specimen with thick, well-spaced ribs. Level 8A, Mariae Zone, Scarburgense Subzone, n°DF 694: Saint-Pierre d'Argençon.

13. *Peltoceratoides athletoïdes* (LAHUSEN), morph *athletoïdes* Lahusen (M). Level 8B, Mariae Zone, Scarburgense Subzone, middle of the *scarburgense* Biohorizon, n°DF 19523: Saint-Pierre d'Argençon.

14a, b. *Cardioceras scarburgense* YOUNG & BIRD, thick specimen. Level 8B, Mariae

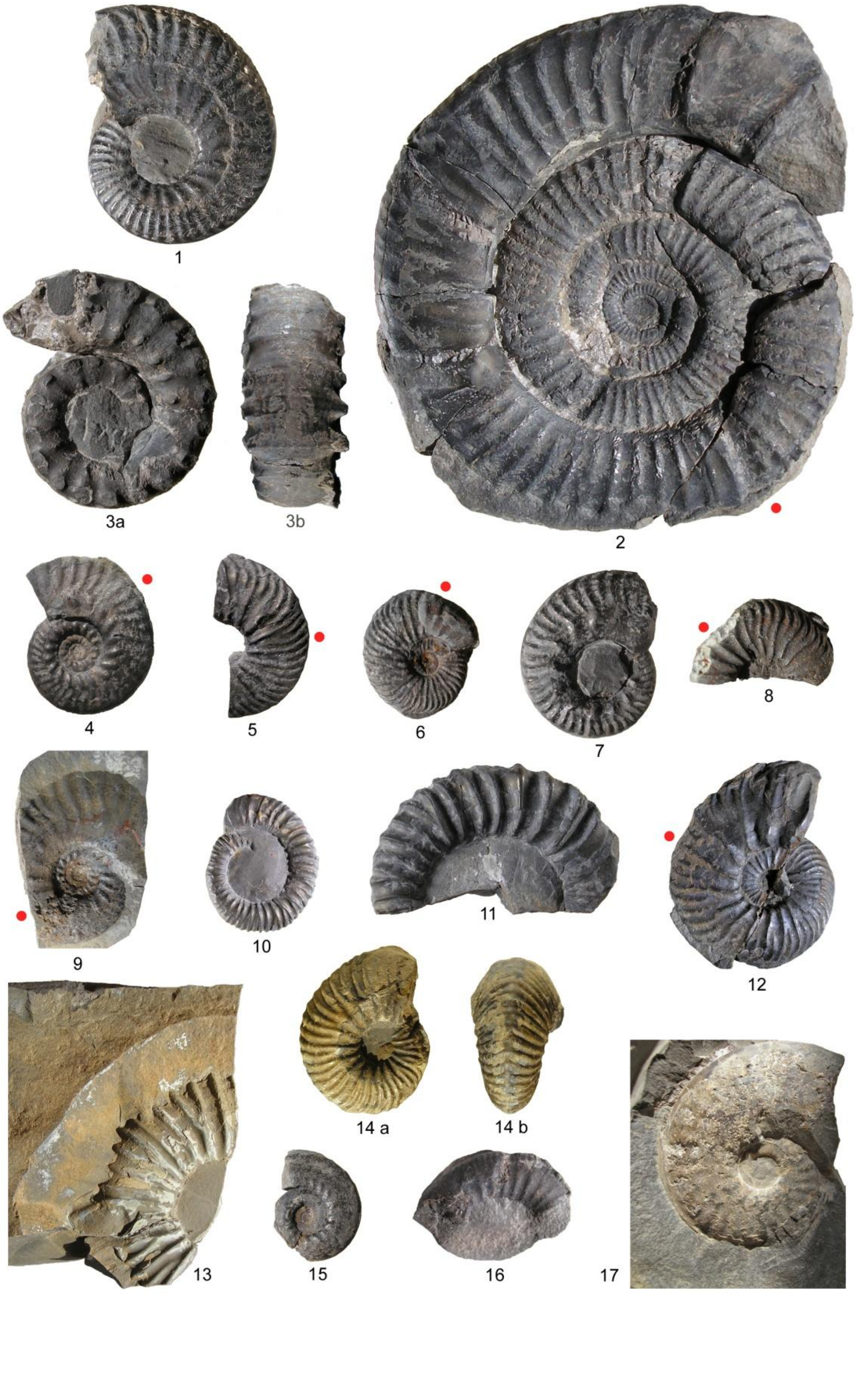
Zone, Scarburgense Subzone, middle of the *scarburgense* Biohorizon, n°DF 19534: Saint-Pierre d'Argençon.

15. *Hecticoceras (Brightia) chatillonense* de LORIOL (M). Level 8B, Mariae Zone, Scarburgense Subzone, middle of the *scarburgense* Biohorizon, n°DF 19530, Saint-Pierre d'Argençon.

16. *Mirosphinctes sp.* Level 9, Mariae Zone, Scarburgense Subzone, top of the *scarburgense* Biohorizon, n° DF 19539: Saint-Pierre d'Argençon.

17. *Eochetoceras villersensis* d'ORBIGNY (M). Level 9, Mariae Zone, Scarburgense Subzone, top of the *scarburgense* Biohorizon, n°DF 19513: Saint-Pierre d'Argençon.

Specimens are from the collection of D. Fortwengler (photographs by D. Fortwengler and plates by Simone Dutour). Scale x 1. Red dot: end of phragmocone.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Milankovitch and sub-Milankovitch forcing of the Oxfordian (Late Jurassic) Terres Noires Formation (SE France) and global implications

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ABSTRACT

High-resolution analysis (2277 samples) of magnetic susceptibility (MS) was performed on ~700-m-thick Early–Middle Oxfordian marine marls of the Terres Noires Formation, SE France. MS variations within these sediments record sub-Milankovitch to Milankovitch frequencies with long-term eccentricity (405 kyr and ~2 Myr) being the most prominent. The 405 kyr cycle was used as a high-resolution geochronometer for astronomical calibration of this poorly constrained interval of Late Jurassic time. The estimated duration of this Early–Middle Oxfordian interval concurs with the current International Geologic Time Scale GTS2004 (~4 Myr), but the estimated durations of the corresponding ammonite zones are notably different. The calibration improves the resolution and accuracy of the M-sequence magnetic anomaly block model that was previously used to establish the Oxfordian time scale. Additionally, the 405 kyr cyclicity is linked to third-order sea-level depositional sequences observed for Early–Middle Oxfordian time. Strong ~2 Myr cycles are consistent with long-term eccentricity modulation predicted for the Late Jurassic. These cycles do not match second-order sequences that have been documented for European basins; this raises questions about the definition and hierarchy of depositional sequences in the Mesozoic eustatic chart. Our results require substantial revisions to the chart, which is frequently used as a reference for the correlation of widely separated palaeogeographic domains. Finally, a long-term trend in the MS data reflects a progressive carbonate enrichment of the marls expressing an Early Oxfordian global cooling followed gradually by a warming in the Middle Oxfordian. This trend also records a major transgressive interval likely peaking at the Transversarium ammonite zone of the Middle Oxfordian.

INTRODUCTION

It has been widely demonstrated that Earth's orbital (Milankovitch) parameters (precession, obliquity and eccentricity) control Earth's climate change through variations in insolation (e.g. Hays *et al.*, 1976; Imbrie *et al.*, 1984). Research has highlighted Milankovitch band periodicities not only in Cenozoic sediments but also in Mesozoic and Palaeozoic sediments, from both platform and basinal realms, and during both icehouse and greenhouse times (e.g. D'Argenio *et al.*, 2004; Hinnov & Ogg, 2007). Long-period modulations in the obliquity and eccentricity, i.e. ~1.2 and ~2.4 Myr, have also been recognized in the sedimentary record, and apparently have a significant influence on global climate (e.g. Beaufort, 1994; Olsen & Kent, 1999; Zachos *et al.*, 2001a, b; Pälike *et al.*, 2006; Mitchell *et al.*, 2008) and sea-level change (e.g. Lourens & Hilgen, 1997; Matthews & Frohlich, 2002).

The discovery of a possible link between orbital variations and sea-level depositional sequences may improve the definition of orders of depositional sequences. For example, the stable 405 kyr orbital eccentricity cycle (Laskar *et al.*, 2004) has been demonstrated to control the third-order depositional sequences in Jurassic and Cretaceous sedimentary records (Strasser *et al.*, 2000; Gale *et al.*, 2002; Boulila *et al.*, 2008a), indicating that orbital forcing plays a major role in sedimentation processes via sea-level change.

In other respects, sub-Milankovitch (millennial) scale cyclicity has also been highlighted in Quaternary

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and pre-Quaternary sediments (e.g. Park *et al.*, 1993; McIntyre & Molfino, 1996; Ortiz *et al.*, 1999; Reuning *et al.*, 2006). The origins of this variability are not well understood. Hemi-precession (i.e. 10–12 kyr periodicities, e.g. Hagelberg *et al.*, 1994; Sun & Huang, 2006) has been explained as due to the twice-yearly passage of the Sun across the intertropical zone (e.g. Berger & Loutre, 1997). Periods of shorter than 10 kyr have been attributed to harmonics of precession (e.g. Berger *et al.*, 2006) or combination tones of primary orbital components (e.g. Yiou *et al.*, 1991). Modelling also predicts that sub-Milankovitch variability can arise from a nonlinear response to Milankovitch forcing (e.g. Short *et al.*, 1991). In this paper, we demonstrate that sub-Milankovitch cyclicity with possibly predominant hemi-precessional frequencies occurred in the Oxfordian (Late Jurassic) marine marls of the Terres Noires Formation.

The Early–Middle Oxfordian is a key period of the Late Jurassic time, for which the sedimentary record indicates significant changes in global climate and sea level (e.g. Hallam, 2001; Dromart *et al.*, 2003; Cecca *et al.*, 2005; Collin *et al.*, 2005; Louis-Schmid *et al.*, 2007; Ramajo & Aurell, 2008). The Late Callovian/Early Oxfordian was a time of cooling associated with a global carbonate production crisis. This crisis has been recognized by a worldwide disappearance of carbonate platforms and the appearance of condensed sequences with iron ooids, or by the deposition of very thick clayey and marly sequences. The Middle Oxfordian corresponds to a period of warming and the start of the carbonate production recovery and the establishment of new carbonate platforms. Nevertheless, there is deep controversy with regard to the interpretation of global sea-level during this time interval. Some have attributed the Early–Middle Oxfordian interval to a major regression (e.g. Jacquin *et al.*, 1998; Hallam, 2001). Others have argued that lowstand conditions occurred in the Early Oxfordian, and favour a major transgression at that time (e.g. Aurell *et al.*, 2003; Dromart *et al.*, 2003; Ramajo & Aurell, 2008).

Very long stratigraphic sequences are necessary to cover the full range of scales of climate change. Effective investigation requires high-resolution analysis of a palaeoclimatic proxy in sedimentary sequences without significant hiatuses. Boulila *et al.* (2008b) performed a high-resolution cyclostratigraphic study on 333-m-thick interval of marine marls of the Terres Noires Formation (Aspres-sur-Buëch, Vocontian Basin, SE France). Here, we have extended this cyclostratigraphic study to a ~700-m-thick interval. The interval involves three composite sections (Aspres-sur-Buëch, Oze and Trescléoux) encompassing the Early–Middle Oxfordian. This very thick extended sequence was studied with the following objectives:

- to document millennial to long-term orbital frequency bands in the Oxfordian Terres Noires Formation (SE France);
- to orbitally calibrate the duration of the Early–Middle Oxfordian time scale and corresponding ammonite zones, in order to improve the International Geological Time Scale (GTS2004, Gradstein *et al.*, 2004);
- to compare low-frequency Milankovitch cycling to the third-order depositional sequences of previous studies, and determine if there are links between astronomical forcing and sea-level change; and
- to better understand global climate and sea-level changes during this key Late Jurassic interval.

GEOLOGIC AND STRATIGRAPHIC SETTING

The Vocontian Basin of SE France is renowned for its fossiliferous Jurassic strata. The abundant ammonites define the Sub-Mediterranean zonal standard for correlation. During the Late Jurassic, the Vocontian Basin (Fig. 1) was situated on the northern edge of the Tethyan Ocean and was connected to the North Atlantic Ocean (Dardeau *et al.*, 1988; Graciansky & Lemoine, 1988). Deposition in the basin centre was fairly continuous, and the relative contributions of carbonate and terrigenous clastics were modulated by climate and sea-level on the surrounding margins. Several hundred of metres of marly sediment comprising the Terres Noires Formation were deposited in the central Vocontian Basin (e.g. Graciansky *et al.*, 1999).

The studied sections crop out at three sites at Aspres-sur-Buëch, Oze and Trescléoux in the Vocontian Basin (Fig. 1). They are present in continuously exposed intervals with a well-constrained ammonite biostratigraphic framework, encompassing the Early–Middle Oxfordian (Fortwengler & Marchand, 1994; Gaillard *et al.*, 1996, 2004; Pellenard *et al.*, 2003). The lithologies are mainly composed of grey marls with a slight enrichment in carbonate up to the Middle Oxfordian. This carbonate enrichment occurred gradually, and in the uppermost part of the Transversarium ammonite zone, is observed as an alternation of marls and marly limestone beds. The three sections are described in detail in the following sections.

Aspres-sur-Buëch

The Aspres-sur-Buëch section (Fig. 2a) is ~333 m thick and spans the Mariae ammonite zone of the Early Oxfordian. The lithology is composed of grey marls with low carbonate content (10–32%) and low amounts of organic matter derived from terrestrial erosion (Tribovillard, 1986, 1988). A carbonate enrichment of the marls is observed in the uppermost part of the section. Calcareous nodules are rare in the lower part of the section, and abundant from ~180 to ~280 m. Subtle colour variations in darkness vs. lightness are occasionally observed in the lower part of the section; these become prominent towards the top of the section due to the increase in carbonate content. Finally, three intervals with distal tempestites (each 1–2 cm thick) were recognized within the marls (labelled T1–3, Fig. 2a). The Aspres-sur-Buëch section was studied by Boulila *et al.* (2008b), who recognized a rich suite of orbital frequencies (precession, obliquity and eccentricity),

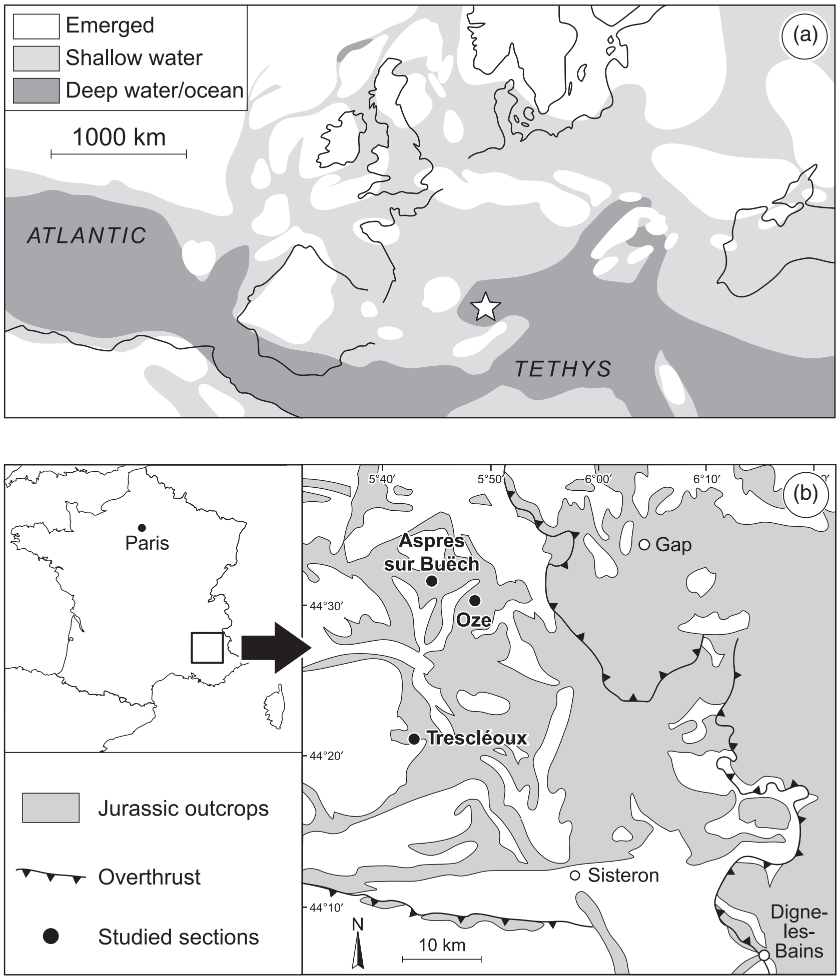

Fig. 1. Palaeogeographic framework of the Vocontian Basin of SE France (indicated with the star in A) during the Late Jurassic and location of the studied sections. (a) Palaeogeographic map of the Tethyan Basin during the Late Jurassic (modified from Ziegler, 1988 in Louis-Schmid *et al.*, 2007). (b) Current geographic and geologic map shows the location of the studied sections (Aspres-sur-Buëch, Oze and Trescléoux) (from the Geologic map of France, 1/1000 0000, BRGM, 6th edition, 2003).

with the 405 kyr eccentricity component being the most prominent.

Oze

The Oze section (Fig. 2b) is ~347 m thick and spans the Mariae ammonite zone *p.p.* of the Early Oxfordian to the base of the Transversarium Zone of the Middle Oxfordian. The lower part of the section (0–70 m) consists of grey marls with rare calcareous nodules and abundant discontinuous nodular beds, reddish in colour. The upper part (~70–347 m) shows alternations of light/dark grey marls associated with an increase in carbonate content. This part also locally displays calcareous nodules and reddish nodular levels. Five bentonite deposits were discovered (Fig. 2b, labelled B1–3, Mbo and B5; Pellenard *et al.*, 2003) and used for regional correlation. As at Aspres-sur-Buëch, the uppermost part of the Mariae Zone records a net carbonate enrichment of the marls. The top of the section is characterized by two thick beds (1.55 and 2.5 m) of marly limestone corresponding to the base of Transversarium ammonite zone (beginning of the so-called *Argovien facies*). The upper bed corresponds to the lithostratigraphic marker R1, which has been recognized in several other sections in the Vocontian Basin (Gaillard & Rolin, 1988; Gaillard *et al.*, 1996).

Trescléoux

The Trescléoux section was previously studied in terms of sequence stratigraphy and regional correlation (Gaillard *et al.*, 1996, 2004). It is a ~110-m-thick interval encompassing the Transversarium Zone of the Middle Oxfordian (Fig. 2c). The interval belongs to the so-called *Argovien facies*, and is characterized by an alternation of marlstones and marly limestones. A composite section including this interval (Transversarium Zone) and another outcropping interval at Oze, including the Plicatilis Zone *p.p.* of the Middle Oxfordian, was previously studied in terms of isotope stratigraphy (Louis-Schmid *et al.*, 2007). Louis-Schmid and colleagues described a positive carbon-isotope excursion at the base of Transversarium Zone, and related this to a perturbation in the global carbon cycle due to a change in global oceanic circulation, that was triggered by major plate tectonic motions. Bentonite mineralogy was studied at an equivalent section at Trescléoux, about 500 m from the present section (Pellenard *et al.*, 2003). The present section records marly limestone beds, some of which are lithostratigraphic markers used for

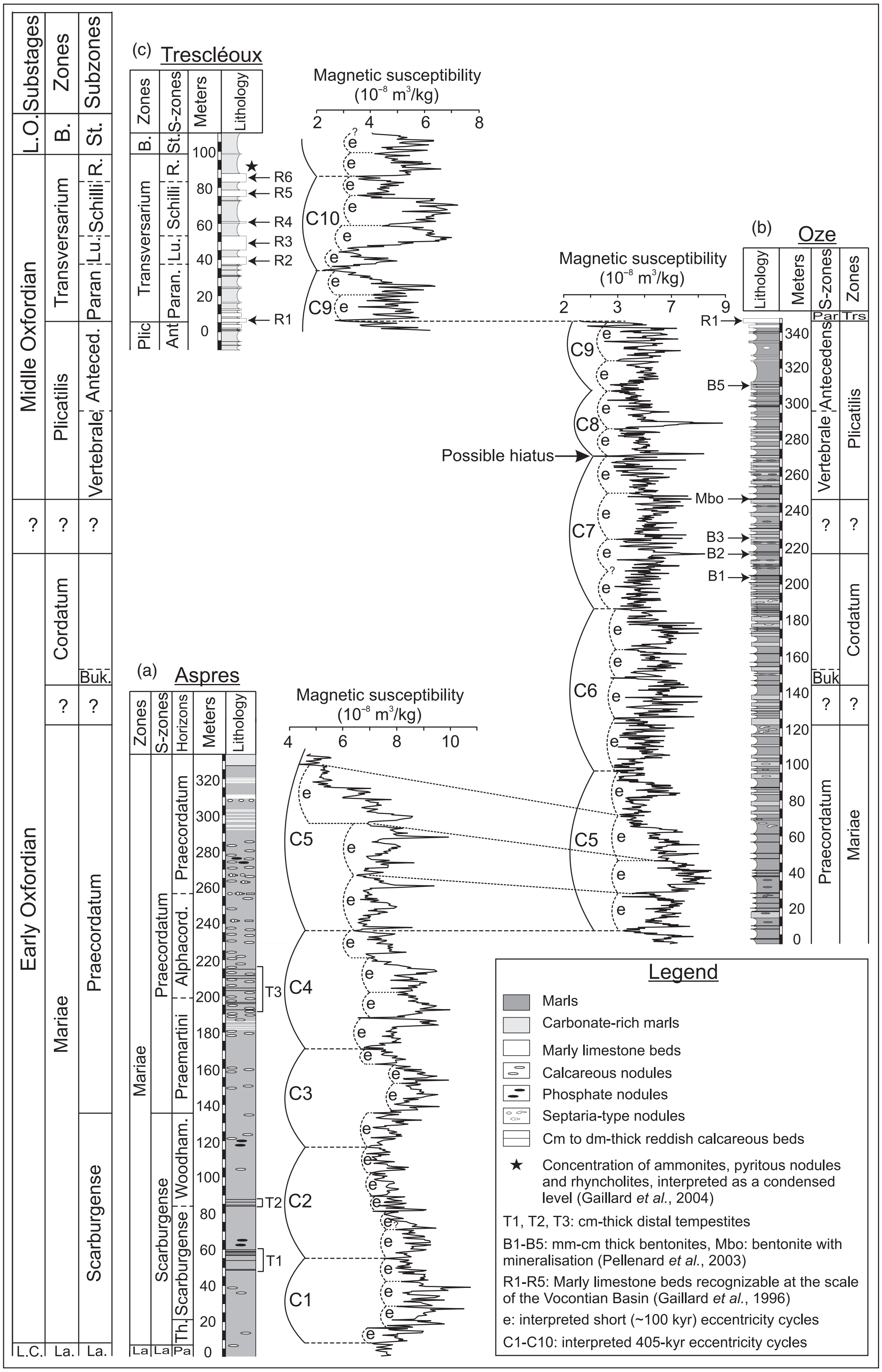

Fig. 2. Stratigraphy and magnetic susceptibility (MS) variations in the studied sections of the Vocontian Basin (SE France). (a) Aspres-sur-Buëch, (b) Oze and (c) Trescléoux. C1–10 cycles are interpreted as 405 kyr orbital eccentricity cycles; 'e' cycles are interpreted as short (~100 kyr) eccentricity cycles. Abbreviations used in biostratigraphic columns: Substages: L.C., Late Callovian; L.O., Late Oxfordian; ammonite Zones: La., Lamberti; B., Bifurcatus; ammonite Subzones: La., Lamberti, Buk., Bukowski; Paran., Parandieri; Lu., Luciaeformis; R., Rotoides; St., Stenocycloides; ammonite Horizons in (a): Pa., Paucicostatum; Th., Thuouxensis; Woodham., Woodhammense; Alphacord., Alphacordatum.

regional correlation (labelled R1–5, Gaillard & Rolin, 1988; Gaillard *et al.*, 1996; Fig. 2c). A concentration of ammonites, pyrite-rich nodules and rhyncholites was recognized within the Rotoides Subzone (see 'star' at ~90 m, Fig. 2c). This level was interpreted by Gaillard *et al.* (2004) as a condensed interval.

METHODS

Magnetic susceptibility (MS)

MS measures the ability of a substance to acquire magnetization when a small external magnetic field is applied (e.g. Evans & Heller, 2003). Different behaviours of magnetic minerals are categorized according to their MS values (Walden *et al.*, 1999). In marine sediments, iron oxides such as magnetite and maghaemite are ferrimagnetic and have strong positive MS. Clays and pyrite are paramagnetic and characterized by weak positive MS. Calcium carbonate and quartz are diamagnetic and have very weak negative MS. Variations in MS in marine sequences therefore reflect variations in lithology that can include paramagnetic clays diluted in various proportions by carbonate (e.g. Mayer & Appel, 1999; von Dobeneck & Schmieder, 1999; Malder *et al.*, 2004) and/or variations in fluxes of ferrimagnetic minerals (e.g. Ellwood *et al.*, 2000). These mineral fluxes to the basin may have been driven by climate changes that in turn were orbitally controlled. MS has proven to be an effective tool in cyclostratigraphy (e.g. Shackleton *et al.*, 1995; Weedon *et al.*, 1999; Huret, 2006; Boulila *et al.*, 2008b) and for the correlation of the pelagic and hemipelagic sedimentary record (e.g. Ellwood *et al.*, 2000; Boulila *et al.*, 2008a).

Sampling was performed at high resolution on these marls, whereas tempestite, bentonite and nodule levels were not sampled since these event beds could introduce spurious MS peaks. The Aspres-sur-Buëch section was sampled previously at 0.5-m intervals (667 samples, Boulila *et al.*, 2008b). Likewise, the Trescléoux section was sampled every 0.5 m (220 samples). The Oze section was sampled at finer intervals of 0.25 m (1390 samples) to recover the sub-Milankovitch (millennial) frequency band. All samples were measured using a Kappabridge KLY-2. Each sample was measured three times, and the mean of these values is reported after weight normalization. The standard deviation of triplicate measurements is always $<0.0091 \times 10^{-8}\,m^3\,kg^{-1}$.

Time-series analysis

405 kyr eccentricity tuning

Orbital tuning is problematic for Mesozoic sedimentary sequences. The main problem is lack of accurate orbital solutions (Laskar *et al.*, 2004) that can be used for high-precision tuning stratigraphy older than about 50–60 Ma. Fortunately, the 405 kyr orbital eccentricity term can be estimated with high accuracy throughout the Mesozoic Era (Laskar *et al.*, 2004). Therefore, we tuned this composite MS dataset to interpreted 405 kyr eccentricity cycles. The 405 kyr time calibration of these data is discussed in detail in 'Results'. The output 405 kyr tuned MS time series is then examined for the presence of other frequencies associated with orbital eccentricity, obliquity and the precession index, and other sub-Milankovitch terms.

Amplitude modulation (AM) analysis

AM analysis of cyclostratigraphic records is an effective means to assess astronomical forcing. One well-known modulation phenomenon is expressed by the precession index, which is modulated by the eccentricity. Moreover, short eccentricity cycles are modulated by long eccentricity terms, which can also be registered in the stratigraphic signal. Obliquity modulation also appears in the astronomical signal, although its origin is complicated (Mélice *et al.*, 2001) and unknown for Jurassic times (Laskar *et al.*, 2004).

According to astronomical theory (Laskar *et al.*, 2004), short (~100 kyr) eccentricity is modulated by 405 kyr and the longer ~2.4 Myr term, the 405 kyr term is modulated by the ~2.4 Myr term and the precession index is modulated by all eccentricity terms. To measure these effects, (1) we bandpass filtered the data to isolate short eccentricity and applied the Hilbert transform (e.g. Hinnov, 2000) to extract the AM of the filtered series; and (2) we computed the power spectra of the output AM curves of the short eccentricity to look for significant frequency components that could represent long-term eccentricity.

Spectral analysis and significance testing

Linear and irregular long-term trends in the MS series were measured and subtracted by the weighted average LOWESS method (e.g. Fig. 3; Cleveland, 1979). Following removal of the trends, the data were analysed via spectral analysis using the multitaper method (MTM, Thomson, 1982) as implemented in the SSA-MTM Toolkit (Ghil *et al.*, 2002).

Assessment of the relative contributions of signal vs. noise in the MS series presents a special challenge. Long-term cycles overwhelmingly dominate all three sections (Figs 2 and 3); other regular, higher-frequency variations are also quite visible. This rather obvious presence of narrow-band (nonrandom) signal precludes application of traditional approaches to noise modelling. For example, a simple autoregressive (e.g. 'red noise') approach (e.g. Box & Jenkins, 1976) would include signal variance in the modelled noise. Narrow-band signal components in the time series should be minimized before noise modelling (Mann & Lees, 1996). This is accomplished through 'median-smoothing' the spectrum to suppress elevated power in narrow bands, then fitting a first-order autoregressive spectral model to this median-smoothed spectrum. The fitted output provides a 'robust' estimate of the noise continuum. We used the SSA-MTM Toolkit to perform robust noise modelling on tuned versions of the MS series.

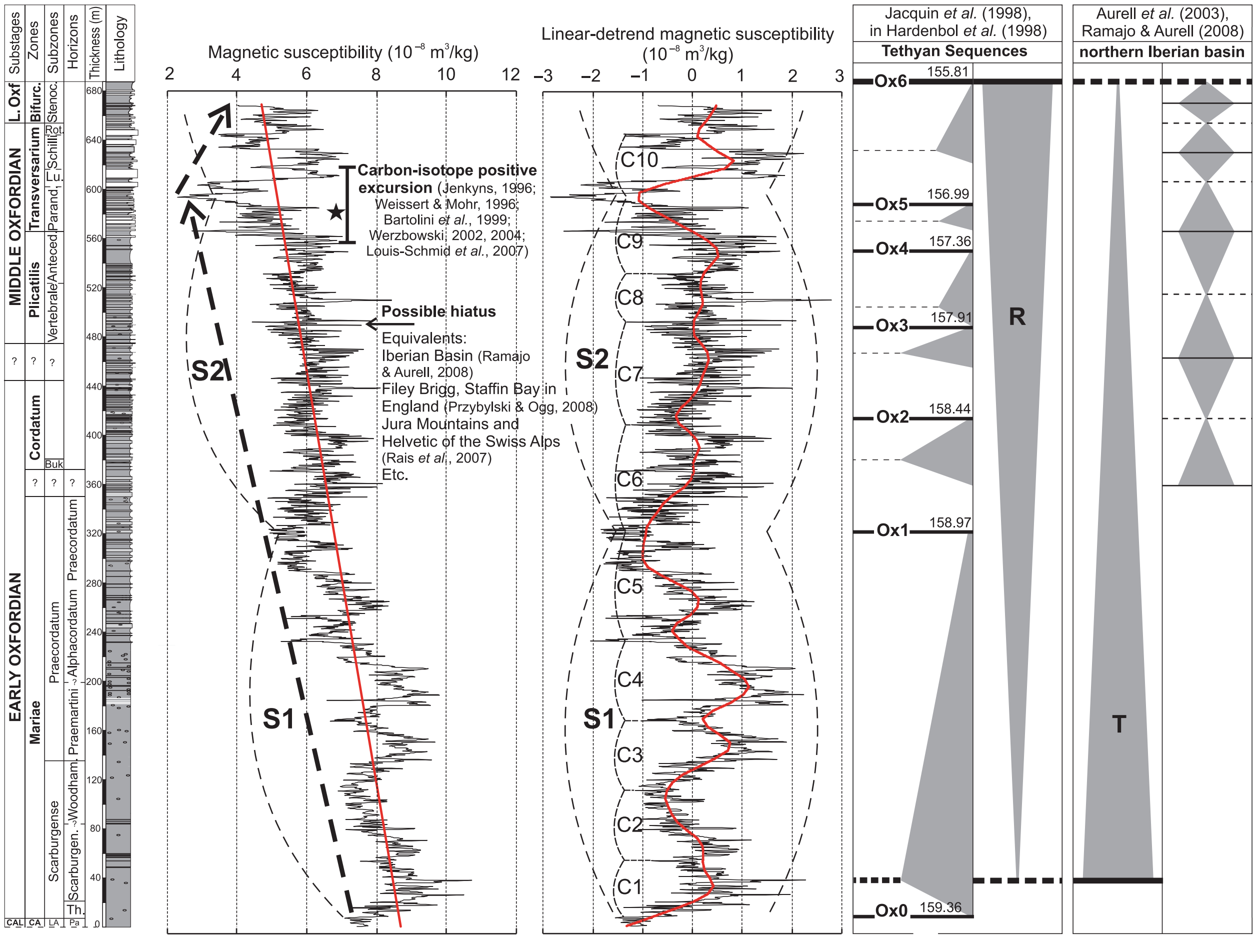

Fig. 3. Stratigraphy and magnetic susceptibility (MS) composite curve of the Early–Middle Oxfordian in the Terres Noires Formation (Vocontian Basin, SE France), and correlations with previous sequence stratigraphic interpretations. Left curve: Raw MS and its linear trend, S1 and S2 indicate the long-term (~2 Myr) eccentricity cycles. The position of the known carbon-isotope excursion around the base of the Transversarium Zone is also shown, with the maximum of the excursion indicated by the black star (from Louis-Schmid *et al*., 2007). Possible hiatus in the Plicatilis Zone and its equivalents in other basins are also mentioned. Right curve: Linear-detrended MS, C1–10 represent the interpreted 405 kyr eccentricity cycles. Eight percent weighted average of the series, obtained using the LOWESS method (Cleveland, 1979), is also shown. Sequence stratigraphic interpretations: from Jacquin *et al*. (1998), first column: third-order sequences, second column: Regressive second-order hemi-cycle (R); from Aurell *et al*. (2003) and Ramajo & Aurell (2008), first column: high-frequency sequences, second column: Major transgressive hemi-cycle (T). Controversies in the major hemi-cycle interpretation are discussed in the text.

RESULTS

MS variations

The MS values in the Terres Noires Formation are relatively low (Fig. 2): 4.36–10.74 × $10^{-8}\,m^3\,kg^{-1}$ in Aspres-sur-Buëch section, 3.60–8.92 × $10^{-8}\,m^3\,kg^{-1}$ in Oze and 2.24–7.21 × $10^{-8}\,m^3\,kg^{-1}$ in Trescléoux. This range of MS values is characteristic of paramagnetic behaviour from the clayey and marly sediments. In the Aspres-sur-Buëch section, there are five low-frequency cycles (C1–5) superimposed on high-frequency cycles (e) (Fig. 2a). The C5 cycle *p.p.* is recorded in the uppermost part of Mariae ammonite zone of the Early Oxfordian (Fortwengler & Marchand, 1994), and is also registered in the Oze section with a similar pattern as at Aspres-sur-Buëch. Ammonite biostratigraphy and MS variations allow us to correlate the overlapping interval (Fig. 2a and b). The Oze section continues registering cycles C5–9 in the overlying ammonite zones (Cordatum and Plicatilis) of the Early and Middle Oxfordian (Fig. 2b). A disrupted interval in the MS C-cycle pattern occurs in the Vertebrale Subzone (Plicatilis Zone) at Oze, suggesting a hiatus comprising half of the C8 cycle (Boulila, 2008; see 'Discussion'). The lower part of the C9 cycle is recorded in the Oze section and its upper part in the Trescléoux. The correlation between Oze and Trescléoux sections is easily performed owing to the lithostratigraphic R1 marker present in both sections. The R1 level is composed of a limestone bed and corresponds to the base of the Transversarium ammonite zone of the Middle Oxfordian (Gaillard & Rolin, 1988; Gaillard *et al*., 1996). MS variations across the Transversarium lower boundary show similar high-frequency variations in both sections. Finally, the Trescléoux section continues registering cycles C9 and C10 (Fig. 2c). In this section, MS records pronounced high-frequency cycles ('e') most likely due to the net enrichment of the marls with carbonate.

The hiatus inferred from the disrupted C8 cycle in the Plicatilis Zone (Fig. 3) is probably not a local event. Stratigraphic gaps (hiatuses) have been observed in the ammonite record in the late Cordatum and Plicatilis Zones in the northern Iberian basin (Ramajo & Aurell, 2008). Similar equivalent stratigraphic gaps have also been recognized in England (Filey Brigg and Staffin Bay), in the Plicatilis Zone (Przybylski & Ogg, 2008). In the Jura Mountains and in the Helvetic of the Swiss Alps, these gaps are expressed as submarine hardgrounds in the Plicatilis Zone (Rais *et al*., 2007). The widespread stratigraphic gaps in the Plicatilis ammonite zone (Middle Oxfordian) may represent a response to a global tectonic event (Louis-Schmid *et al*., 2007; Rais *et al*., 2007) leading to sea-level rise, and consequently, interruption of clay deposition in the Vocontian Basin.

Cyclostratigraphic analysis

The composite section of MS variations

The overlapping three Terres Noires sections allows construction of a composite MS series covering the Early–Middle Oxfordian (Fig. 3). MS variations show a long-term decreasing trend up to the Middle Oxfordian (lower part of the Transversarium Zone), associated with a progressive carbonate enrichment of the marls, i.e. dilution from diamagnetism. There are two very low-frequency cycles (S1 and S2) superimposed on the C1–10 cycles; shorter 'e' cycles also occur within C1–10 cycles throughout the composite series. Figure 4 displays the composite MS series together with the ammonite zones, and quantitatively defines the C1–10 cycles with the aid of low-pass filtering. As discussed further below, the C1–10 cycles play a key role in our development of an astronomical time scale for this Early–Middle Oxfordian interval.

Spectral analysis of the untuned MS composite section (Fig. 5a) shows the presence of numerous significant frequencies, resulting, in part, from a highly variable sedimentation rate. Notable wavelengths with spectral peaks exceeding the 99% confidence level (CL) of the modelled noise include 273, 70, 30–46, 16–22, 10–13 m and numerous wavelengths in the 2–4 m range. The 16–22 m wavelengths are associated with the 'e' cycles that persist through the

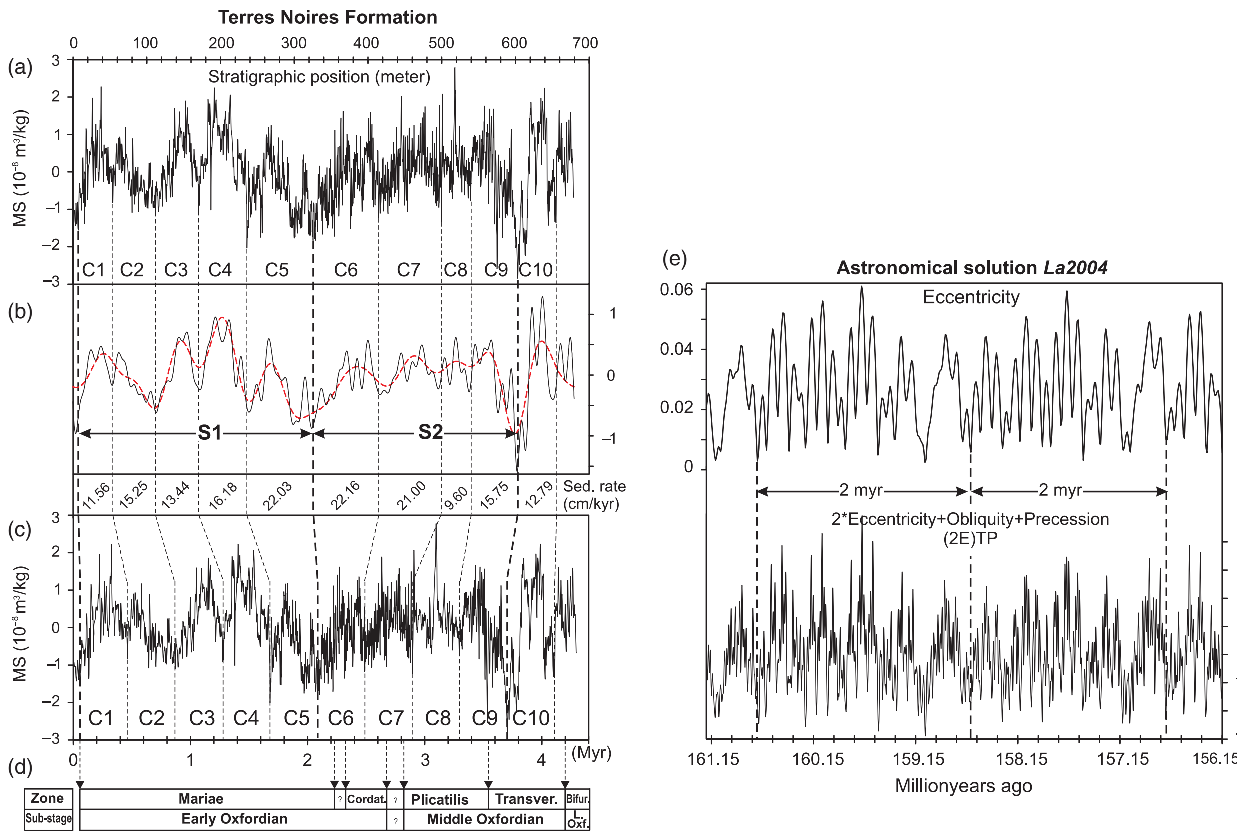

Fig. 4. 405-kyr orbital calibration of the magnetic susceptibility (MS) variations of the Early–Middle Oxfordian in the Terres Noires Formation (Vocontian Basin, SE France). (a) Linear-detrended raw MS series. (b) Identification of MS low-frequency cycles. Dashed curve: Low-pass filtered MS series to recover long-term C1–10 and S1–2 cycles (0–0.022 cycles m^{-1} band), Solid curve: Low-pass filtered MS series to recover 'e' C1–10 and S1–2 cycles (0–0.091 cycles m^{-1} band). (c) Linear-detrended tuned MS series. C1–10: interpreted 405 kyr eccentricity cycles, S1 and S2: interpreted ~2 Myr eccentricity cycles. Sedimentation rates from the 405 kyr orbital tuning are also shown. (d) Biostratigraphic data. Ammonite zones: Cordat., Cordatum; Transvers., Transversarium; Bifur., Bifurcatus. Sub-stages: L. Oxf., Late Oxfordian. The 405 kyr astronomically calibrated time axis is projected onto the ammonite zone boundaries to estimate the duration of the Early–Middle Oxfordian and the corresponding ammonite zones (see Table 1). (e) Upper curve: nominal La2004 eccentricity model over 156.15–161.2 Ma. Lower curve: composite La2004 orbital parameters [eccentricity, obliquity (tilt), precession index] over 156.15–161.2 Ma, reported in (2E)TP format (e.g. Imbrie *et al*., 1984).

Table 1. Comparison between ammonite zone duration estimates (in myr) of Early-Middle Oxfordian (Late Jurassic) derived from cyclostratigraphy of the Terres Noires Formation of SE France (this study) and the Geologic Time Scale GTS2004 (Gradstein *et al.*, 2004).

GTS2004 (Gradstein *et al.*, 2004)			
Age in Ma	Substages	Ammonite zones	Durations
158	Middle Oxfordian	Transversarium	1.2 ± 0.4
	Middle Oxfordian	Plicatilis	0.9 ± 0.2
160	Lower Oxfordian	Cordatum	1.1
161.2 ± 4.0	Lower Oxfordian	Mariae	0.6
		Total	3.8 ± 1.2/1.4

This study	
Durations	Ammonite zones
0.65	Transversarium
0.72–0.87	Plicatilis
0.35–0.60	Cordatum
2.2	Mariae
4.07	Total

composite section (Fig. 3); the 30–46 m wavelengths appear intermittently bundling two 'e' cycles (see Fig. 2c, for example); the 70 m wavelength indicates the C1–10 cycles, and the 273 m peak the S1–S2 cyclicity.

Assignment of 405 kyr eccentricity to C1–10 cycles

According to GTS2004, the Early–Middle Oxfordian interval has a duration of 3.8 ± 1.4 Myr. This calculation is based on a seafloor spreading-rate model of the Hawaiian ridge in the Pacific of $\sim$28 km Myr^{-1} (Ogg & Smith, 2004). Constraints from Early Cretaceous cyclostratigraphy (Huang *et al.*, 1993) imply $\sim$30 km Myr^{-1}, providing independent confirmation of the spreading model and the early M-Sequence time scale. Thus, the 10 C1–10 MS cycles have approximately 400 kyr durations, i.e. very close to 405 kyr scale eccentricity. The strong expression of four 'e' cycles within each of the C1–10 cycles is further suggestive of a 100–400 kyr relationship between 'e' and 'C' cyclicity; the superposed very long-term S1–S2 cycles suggests the possible presence of a long-term ($\sim$2 Myr) eccentricity variation, although tectonic processes, which operate at multimillion year scales, cannot be ruled out as a driving force.

These collective observations lead us to calibrate the C1–10 cycles to 405 kyr eccentricity. The assignment of 405 kyr cycles to C1–10 was carried out through guidance of low-pass filtering (Fig. 4b). The vertical dashed lines indicate the boundaries that we have defined for the individual 'C' cycles; these were selected through identification of minima of the 'e' filtered series within the minima defined by the 'C' filtered series. These boundaries also mark the 405 kyr tie points that were used to tune the composite MS section (Fig. 4c).

The Milankovitch band

In the 405 kyr tuned MS spectrum (Fig. 5b), significant peaks are calibrated to Milankovitch frequencies above

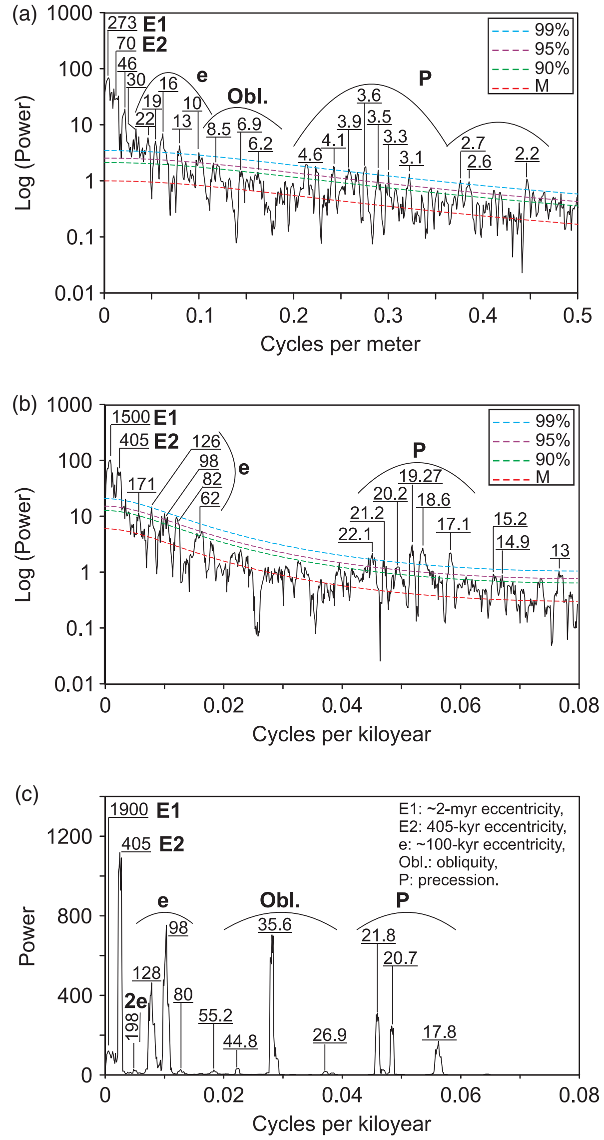

Fig. 5. Time-series analysis of the magnetic susceptibility (MS) variations of the Early–Middle Oxfordian in the Terres Noires Formation (Vocontian Basin, SE France), and comparison with the astronomical solution La2004 (Laskar *et al.*, 2004). Results of robust noise modelling are also shown: Curve M is the median-smoothed, fitted red noise spectrum (see '405 kyr eccentricity tuning'); the upper 90, 95 and 99% confidence limits are also shown. (a) 2π-MTM Log(power) spectrum of raw MS series (curve of Fig. 4a). Robust noise modelling was carried out with a 0.4 cycles m^{-1} median smoothing window, which represents a bandwidth that is 20% of the effective Nyquist frequency (2 cycles m^{-1}, with respect to sampling intervals of Oze section, i.e. 0.25 cm). (b) 2π-MTM Log(power) spectrum of the tuned MS series (curve of Fig. 4b). Robust noise modelling was carried out with a 0.026 cycles kyr^{-1} median smoothing window, which represents a bandwidth that is approximately 20% of the lower boundary of the effective Nyquist frequency range (varying between 0.128 and 0.44 cycles kyr^{-1}) of the series. (c) 2π-MTM power spectrum of the (2E)TP [composite astronomical curve = 2 × Eccentricity + obliquity (Tilt) + Precession] of La2004 for the interval 156.15–161.2 Ma (see Fig. 4c), which approximately corresponds to its time-equivalent in the studied Oxfordian Terres Noires Formation, according to GTS2004 (Gradstein *et al.*, 2004).

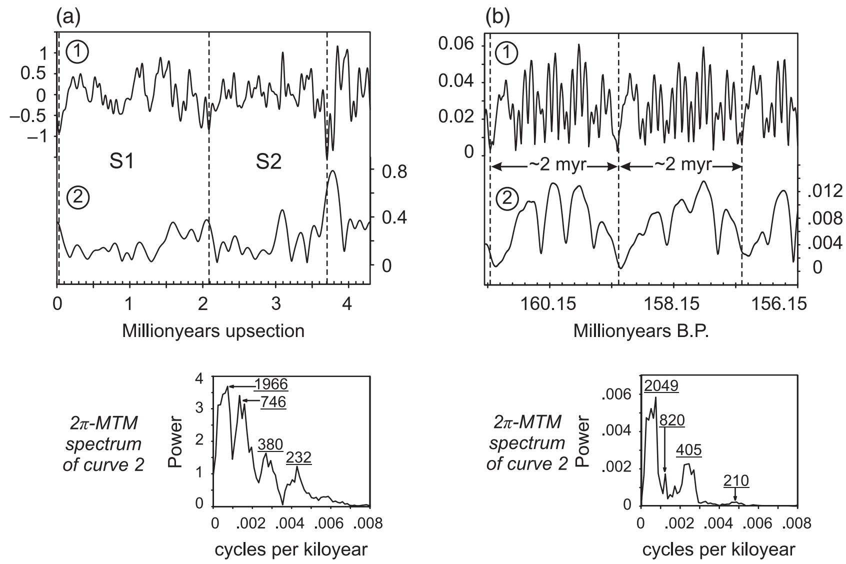

Fig. 6. Amplitude modulations (AM) of magnetic susceptibility (MS) variations of the Early–Middle Oxfordian in the Terres Noires Formation (Vocontian Basin, SE France), and comparison with the AM in the astronomical solution La2004 (Laskar *et al.*, 2004). (a) AM of tuned MS series, curve 1: Low-pass filtered MS series (0–0.0164 cycles kyr^{-1} band), curve 2: AM envelope of the filtered short eccentricity MS series (0.0071–0.0151 cycles kyr^{-1} band), its 2π-MTM power spectrum is shown; S1 and S2 represent interpreted ~2 Myr eccentricity cycles. (b) AM of the short eccentricity in La2004 for the interval 156.15–161.15 Ma, which covers almost two long-term (2.0 Myr) eccentricity modulations, curve 1: Filtered short eccentricity of La2004 (0.0071–0.0161 cycles kyr^{-1} band), Curve 2: AM envelopes of the filtered short eccentricity, its 2π-MTM power spectrum is shown. All filtering was carried out using the Taner filter (Taner, 2000).

the 95% CL, with some exceeding the 99% CL. The 405 kyr calibration of the C1–10 cycles aligns the 60–80 m wavelength peak into a single 405 kyr peak. The persistent 'e' cycles calibrate as short (~100 kyr) eccentricity components aligned at periods of 82, 98 and 126 kyr, which are remarkably close to the predicted astronomical periods (80, 98 and 128 kyr, Fig. 5c). The '2e' cycles (i.e. 30–46 m wavelengths) calibrate to 171 kyr peak, which falls below the 95% CL, likely because this cyclicity appears per intermittence. Its possible analogue in the La2004 solution is 198 kyr periodicity. The precession band in the tuned MS series contains spectral peaks of 17.1, 18.6, 19.27 and 22.1 kyr, all of them exceeding the 99% CL, and close to the predicted astronomical precession periods (17.8, 20.7 and 21.8 kyr). Possible obliquity terms in the depth domain (some reaching 95% CL) fall below 90% CL in the tuned series. The spectral peak with the highest power and 273 m wavelength (Fig. 5a), which corresponds to the average thickness of the S1 and S2 cycles, calibrates to 1500 kyr. Its analogue in the La2004 solution is a low-power ~1900 kyr variation (Fig. 5c).

To explore the behaviour of the eccentricity-scale periodicity, we performed AM analysis on the tuned MS series (Fig. 6a), and on the nominal astronomical solution La2004 calculated for Oxfordian time (Fig. 6b). Our objective is to highlight a close analogy between low-frequency MS variations and orbital eccentricity terms. The low-pass-filtered MS series (Fig. 6a, curve 1) shows strong short (~100 kyr) eccentricity cycles bundled by the 405 kyr cycles, especially in the upper part of the S1 cycle. Spectral analysis of the AM envelope of the MS data short eccentricity band reveals four peaks (1966, 746, 380 and 232 kyr; Fig. 6a), which are closely analogous to the La2004 AM spectral peaks (2049, 820, 405 and 210 kyr; Fig. 6b) of the eccentricity.

The strong similarity between the power spectra of the MS series and the astronomical model (Fig. 6) supports the hypothesis that S1 and S2 reflect long-term eccentricity modulation. One problem is how to explain the ~2 Myr long eccentricity for this Mesozoic interval (Oxfordian, Jurassic) vs. the ~2.4 Myr long eccentricity predicted and detected in Cenozoic strata (e.g. Hilgen *et al.*, 2003). This periodicity is related to the secular frequency $(g_4 - g_3)$, i.e. the interaction between the orbital perihelia of Mars and Earth. Its predicted change from ~2.4 Myr periodicity in Cenozoic times to ~2 Myr in Mesozoic times is related to chaotic motion of the Solar System, and a transition from $(s_4 - s_3) - 2(g_4 - g_3)$ secular resonance to $(s_4 - s_3) - (g_4 - g_3)$ resonance (Laskar, 1999). The La2004 eccentricity from 161.2 to 156.15 Ma (Fig. 4e) indicates a $g_4 - g_3$ periodicity shortened to 2 Myr (Figs 5c and 6b) that is reflected in this Oxfordian sequence. Studies from an older and exceptionally (> 30 Myr) long Triassic–Jurassic sedimentary sequence indicates a $g_4 - g_3$ periodicity of 1.75 Myr (Olsen & Kent, 1999; Olsen, 2008). These and other future studies will help to guide future modelling of these complex ancient Solar System orbital interactions.

Sub-Milankovitch frequencies

Our sampling interval in the Oze section was 25 cm (equivalent to ~1.15 kyr), and allows the detection of sub-Milankovitch frequencies. To highlight the sub-Milankovitch band, we selected the highest resolution tuned interval C5–7 (Fig.

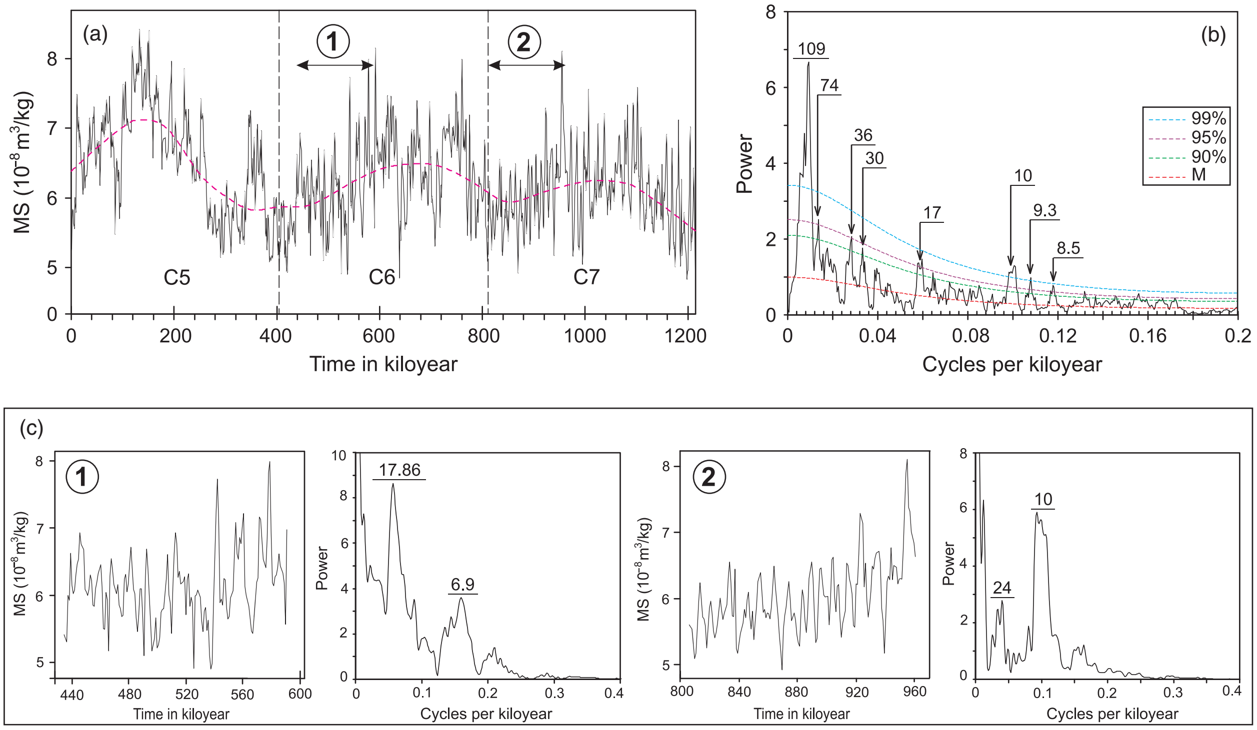

Fig. 7. High-frequency analysis of magnetic susceptibility (MS) variations within the C5–7 interval in the Oze section (Early–Middle Oxfordian, SE France) to highlight the sub-Milankovitch frequency band. (a) Tuned C5–7 series to 405 kyr periodicity (from Fig. 4c). A 20% weighted average of the series, obtained using the LOWESS method (Cleveland, 1979), is also shown. (b) 2π-MTM power spectrum of the tuned MS series after removal of the 20% weighted average of the series in (a). Robust noise modelling is as in Fig. 5, but with a 0.086 cycles kyr^{-1} median smoothing window, which represents a bandwidth that is approximately 20% of the effective Nyquist frequency range (varying between 0.42 and 0.44 cycles kyr^{-1}) of the series. (c) 2π-MTM power spectra of two selected intervals from the tuned C6 (left) and C7 (right) cycles (indicated by arrows in Fig. 7a).

7a), and performed spectral analysis after subtraction of C5–7 cyclicity (Fig. 7b).

A strong significant peak centered on the period of 109 kyr corresponds to the short (~100 kyr) eccentricity; another small peak at 74 kyr, above the 95% CL, may represent a shorter eccentricity term. The two peaks centered on the period of 30 and 36 kyr may represent forcing by obliquity, (cf. Fig. 5c). The peak at 17 kyr, the power of which exceeds the 95% CL, corresponds to the short precession component (17.8 kyr, Fig. 5c). Finally, three significant peaks, which exceed the 95 or 99% CL are centered on the periods of 8.5, 9.3 and 10 kyr, in the sub-Milankovitch frequency band.

These sub-Milankovitch peaks could be artefacts as a consequence of non-sinusoidal lower frequency terms (e.g. Meyers *et al.*, 2001 their Fig. 3) or significant palaeoclimatic cycles (e.g. Park *et al.*, 1993; McIntyre & Molfino, 1996; Ortiz *et al.*, 1999; Reuning *et al.*, 2006; Sun & Huang, 2006; Fischer *et al.*, 2009). Close examination of the C6 and C7 cycles confirm that these high-frequency components are not artefacts, but are actual variations in the MS data. In Fig. 7c, we performed spectral analysis on 150-kyr-long intervals from the C6 and C7 cycles. Within C6, two spectral peaks centered on periods of 17.86 and 6.9 kyr, represent precessional and sub-Milankovitch periodicities. In C7, a strong peak centered on the 10-kyr period corresponds to a hemi-precessional period; a smaller 24-kyr period peak may be of precessional origin.

These sub-Milankovitch periodicities could represent half-precessional cycles (e.g. Park *et al.*, 1993; Berger & Loutre, 1997). Berger & Loutre (1997) explained the occurrence of these hypothetical cycles, as the passage of the Sun twice per year in the intertropical zone. Other studies demonstrated that the effect of these cycles could be transferred from lower latitudes to higher latitudes via seawater surface and atmospheric heat advection (e.g. Hagelberg *et al.*, 1994; McIntyre & Molfino, 1996; Turney *et al.*, 2004).

In the Late Jurassic, the Vocontian Basin was situated in a palaeolatitudinal position between 20 and 25°N (e.g. Cecca *et al.*, 2005), i.e. in an intertropical position. We suggest that a half-precessional influence on the deposition of the marls of the Terres Noires Formation is possible. However, these preliminary results require further investigation to better understand the occurrence and control of sub-Milankovitch cycles on high-frequency climate and on the consequent deposition of the marls of the Terres Noires Formation.

DISCUSSION

Astronomical cycles and the Oxfordian time scale

The C1–10 cycles in the MS series are interpreted to correspond to the 405 kyr orbital eccentricity term. As such, they constitute a high-resolution metronome for astronomical calibration of this Late Jurassic sedimentary series (Laskar *et al*., 2004). We used the tuned C1–10 cycles to estimate the duration of the Early–Middle Oxfordian and the corresponding ammonite zones (Table 1). We projected the 405 kyr astronomically calibrated time axis onto the ammonite zone boundaries (Fig. 4c and d). In Table 1, we have transferred results with sometimes two possible duration estimates (maximum and minimum) whenever there are uncertainty intervals within ammonite zone boundaries. For example, the lower and upper boundaries of the Cordatum ammonite zone are not well recognized. Thus, minimum and maximum durations are given as 0.35 and 0.60 Myr, respectively. Transversarium Zone boundaries are precisely defined at centimetre-scale. Thus, one duration is defined (0.65 Myr). An exception is the Mariae Zone, which has a large uncertainty in its upper boundary, yet only one duration is given (2.2 Myr). This duration is derived from a correlation of the Terres Noires Formation and drill-cores in the eastern Paris Basin, where the Mariae Zone is precisely constrained biostratigraphically (Huret, 2006; Boulila *et al*., 2008b).

The 405 kyr tuned MS series requires a duration of 4.07 Myr for the Early–Middle Oxfordian. This duration is consistent with that given in the GTS2004 (i.e. 3.8 $\pm$ 1.4 Myr, Gradstein *et al*., 2004). However, ammonite zone duration estimates differ notably from GTS2004. For example, the Mariae Zone is estimated as $\sim$2.2 Myr whereas the GTS2004 assigns only 0.6 Myr to this biozone. In contrast, the Cordatum Zone is estimated as shorter (i.e. 0.35–0.60 Myr) than it is in GTS2004 (1.1 Myr).

Estimates of the duration of Oxfordian ammonite zones in GTS2004 were derived from a correlation of outcrop magnetostratigraphy to marine magnetic anomalies, both of which incorporated hidden assumptions and uncertainties. The time scale for the Late Jurassic was based on fitting the M-sequence magnetic anomalies, and their Oxfordian and Callovian extension from deep-tow magnetometer surveys to radioisotopic ages from two ODP sites drilled into Jurassic oceanic crust (Ogg & Smith, 2004). A compilation of Oxfordian and Kimmeridgian magnetostratigraphic studies (Ogg & Gutowski, 1996; Ogg & Coe, 1997) provided an approximate polarity pattern for each ammonite zone. The main problem was that the comparison of the composite magnetostratigraphy to the marine magnetic anomaly target curve incorporated an implicit assumption that the relative thicknesses of adjacent ammonite zones in the outcrops or the relative numbers of component subzones were also an indication of their relative durations. Correlations to the estimated Lower and Middle Oxfordian portion of the marine magnetic pattern were ambiguous, due to the combination of uncertain interpretations of the deep-tow magnetometer observations and the lack of a distinctive ‘fingerprint’ within the relatively frequent and evenly spaced major magnetic reversals. Furthermore, the lower Oxfordian magnetostratigraphic sections from the British Isles and Poland had very condensed strata in the *Quenstedtoceras mariae* zone relative to the overlying *Cardioceras cordatum* and higher zones, which contributed to the scaling of the proposed correlation to this marine magnetic anomaly pattern. Indeed, it is probably fortuitous in GTS2004 that the suite of suggested correlations of the distorted Early and Middle Oxfordian magnetostratigraphy to the constant-rate model for the oceanic anomalies yielded durations for the Oxfordian substages that broadly match those in our cycle-scaled results.

With additional cyclostratigraphic studies of Middle Oxfordian strata, it should possible to reverse this procedure i.e. to scale the outcrop-based magnetostratigraphy to the actual duration of each ammonite subzone, compare this calibrated polarity pattern to the marine magnetic anomaly model and derive actual spreading rates for these Pacific centres (Boulila *et al*., 2008c).

Long-term (405 kyr and $\sim$2 Myr) eccentricity cycles and implications for global climate and sea-level change

Here, we discuss a possible direct link between the highlighted orbital cycles from MS and sea-level depositional sequences from previous studies. In Fig. 3, we compare S1 and S2 and C1–10 MS cycles to the third-order depositional sequences of Graciansky *et al*. (1999) who refer to Jacquin *et al*. (1998) (in Hardenbol *et al*., 1998). S1 matches the third-order sequence [Ox0–Ox1] within the Mariae ammonite zone. However, S2 includes the four following sequences ([Ox1–Ox2], [Ox2–Ox3], [Ox3–Ox4] and [Ox4–Ox5]). The interval from Ox1 to Ox2 (i.e. top of Mariae, Cordatum, Plicatilis and Transversarium ammonite zones) includes four 405 kyr cycles C6–9, which most likely correspond to the four third-order sequences [Ox1–Ox2], [Ox2–Ox3], [Ox3–Ox4] and [Ox4–Ox5].

The exception of [Ox0–Ox1] (which includes five 405 kyr cycles instead of one) within the Mariae Zone leads us to reconsider the sequence stratigraphic interpretation given in the Hardenbol *et al*. (1998) chart. Stratigraphic resolution in the chart is not high enough to provide details at the scale of an ammonite zone. Indeed, the Hardenbol *et al*. chart consists of a compilation of data collected from numerous, worldwide palaeogeographic basins. For the Late Jurassic, Tethyan sequences were mainly established according to well logging in the North Sea and Paris Basin. Sections with reduced sedimentation rates within the Callovian–Oxfordian boundary were used to define the reference eustatic sequences (Jacquin *et al*., 1998). The investigation of condensed stratigraphic sections, combined with the interpretation that condensed clayey intervals represent a single maximum flooding surface, could result in a failure to identify all sequences present within the Mariae Zone. In the Callovian–Oxfordian iron ooid condensed sections of the Paris Basin, Courville & Collin (2002) demonstrated that a condensed interval may include several sea-level variations. A similar problem of missing sequences in the Jacquin *et al*.'s (1998) sequence stratigraphic interpretation of the North Sea and Paris basins was encountered in the Early Kimmeridgian of the Vocontian Basin in which an additional sequence was discovered between the sequence boundaries Kim1 and Kim3 of the chart (Boulila *et al.*, 2008a).

The northern Iberian Basin provides an additional example, in which the Oxfordian is condensed (only 10–20-m-thick sections, Ramajo, 2006, Fig. 3). Ramajo & Aurell (2008) recognized seven third-order sequences (described as higher-order cycles) within the Oxfordian stage, and the Mariae Zone is entirely absent in their sections. A widespread gap across the entire Iberian Basin occurs in the Callovian–Oxfordian transition, which affected the Lamberti and Mariae Zones of the Late Callovian and Early Oxfordian, respectively (Aurell *et al.*, 2003). In these Iberian sections, the interval between Ox1 and Ox5 records three third-order sequences and a half (i.e. the transgressive hemi-cycle of the fourth sequence). Nevertheless, the excellent agreement between the 405 kyr cycles interpreted here (C6–9) and the third-order sequences between Ox1 and Ox5, either in the Hardenbol *et al.* chart or in the Iberian sections (Ramajo & Aurell, 2008) leads us to consider that they are one and the same. The exceptionally thick Mariae Zone in the Terres Noires Formation records five 405 kyr cycles vs. only one third-order sequence considered in Jacquin *et al.* (1998).

In sum, we deduce that third-order sequences reflect 405 kyr eccentricity cycles in the Vocontian Basin during at least the Early–Middle Oxfordian. This idea was previously suggested by Strasser *et al.* (2000) and Boulila *et al.* (2008a) who argued that third-order sequences in the Oxfordian, Early Kimmeridgian and Berriasian to Valanginian in the Swabian and Swiss Jura, and in the Vocontian Basin, were responses to 405 kyr eccentricity cycles.

The long-term ($\sim$2 Myr) eccentricity cycles (S1 and S2) do not fit with the major transgressive/regressive (T/R) hemi-cycle of previous studies (e.g. Jacquin *et al.*, 1998; Aurell *et al.*, 2003). In contrast, the long-term MS trend fits the major T/R hemi-cycle approximately delimiting the Callovian/Oxfordian transition and the Transversarium Zone of the Middle Oxfordian (Fig. 3). However, there is serious controversy surrounding the sequence interpretation of this interval: Jacquin *et al.* (1998) attribute the interval to a major marine regression whereas Aurell *et al.* (2003) argue for a major transgression (Fig. 3). Specifically, Jacquin *et al.* (1998) interpret a major second-order transgressive peak in the earliest Oxfordian (Mariae Zone), and a second-order sequence boundary at the base of Late Oxfordian (Bifurcatus Zone). However, Aurell *et al.* (2003) and Ramajo & Aurell (2008) oppose Jacquin *et al.*'s interpretation: Based on detailed sedimentological studies, Aurell and Ramajo suggested a global sea-level fall in the earliest Oxfordian, and a major transgressive peak at the base of Late Oxfordian (late Bifurcatus Zone).

Our results do not precisely support either of these two models. However, compared with other previous studies we favour the interpretation of Ramajo & Aurell (2008). Long-term MS variations within the Terres Noires Formation provide key arguments about global climate change and possible links with sea-level variations (e.g. Dromart *et al.*, 2003). The original MS curve (Fig. 3, left curve) shows a strong decreasing linear trend through the lower Transversarium Zone. This trend is associated with a net enrichment of the marls with carbonate. The earliest Oxfordian (base of Scarburgense Subzone) registers the highest clay content. However, the Middle Oxfordian (lower part of the Transversarium Zone) records the highest carbonate content within the R2 marker, recognized at several sites of the Vocontian Basin (Gaillard & Rolin, 1988; Gaillard *et al.*, 1996). The loss of carbonate production in the Early Oxfordian was worldwide (e.g. Dromart *et al.*, 1996; Cecca *et al.*, 2005). This global widespread carbonate crisis has been explained by several possible factors such as: (1) a global cooling associated with eustatic lowstand conditions (e.g. Dromart *et al.*, 2003; Cecca *et al.*, 2005; Ramajo & Aurell, 2008), and (2) increasing acidity of the oceans and/or in the atmosphere due to strong volcanic activity (e.g. Jones & Jenkyns, 2001; Díaz-Martínez *et al.*, 2002; Cogné & Humler, 2004). Likewise, the marls of the Terres Noires Formation support a global scale enrichment in carbonate production in the lower part of Transversarium Zone. This recovery of carbonate production was related to a global warming period (e.g. Dromart *et al.*, 2003; Cecca *et al.*, 2005), and was most likely associated with global sea-level rise (e.g. Jenkyns, 1996; Aurell *et al.*, 2003; Louis-Schmid *et al.*, 2007; Ramajo & Aurell, 2008).

Evidence of a cooling period in the earliest Oxfordian, followed by a warming in the Middle Oxfordian has been highlighted by consistent geochemical and biological data from widely distributed sites (e.g. Picard *et al.*, 1998; Podlaha *et al.*, 1998; Riboulleau *et al.*, 1998; Price, 1999; Abbink *et al.*, 2001; Dromart *et al.*, 2003; Cecca *et al.*, 2005; Tremolada *et al.*, 2006). Lowstand sea-level conditions in the earliest Oxfordian have been interpreted from high-resolution sedimentological studies in the northern Iberian Basin (Ramajo & Aurell, 2008) and from biostratigraphic criteria, and especially by the existence of worldwide stratigraphic gaps at the Callovian/Oxfordian transition (Dromart *et al.*, 2003).

In fact, the epicontinental Vocontian Basin of SE France was surrounded by emergent areas during Late Jurassic time (Fig. 1). The Corso-Sarde terrain to the south, the Massif Central to the west, the Ardennaise area to the north and the Briançonnais terrain to the east, were likely sources of detrital components (Debrand-Passard *et al.*, 1984; Dercourt *et al.*, 1993; Pellenard, 2003). The Early–Middle Oxfordian *p.p.* (i.e. S1 and S2 MS cycles) of the Terres Noires Formation registers high sedimentation rates ($\sim$150 m Myr^{-1}) associated with the highest subsidence rates of the Late Jurassic (e.g. Dardeau *et al.*, 1988; Graciansky *et al.*, 1999). In addition, high-resolution sequence stratigraphy in the adjacent Paris Basin shows that the highest rates of accommodation space creation of Mesozoic times occurred in the Middle to Late Oxfordian (Guillocheau *et al.*, 2000). These data together with ours, and following the principles of classic sequence stratigraphy, favour Ramajo and Aurell's transgressive model. Specifically, the maximum of clay content in the lower Mariae Zone (earliest Oxfordian) cannot be explained by a sea-level rise as proposed by Jacquin *et al.* (1998). Flooding of the surrounding emergent areas reduces erosion and consequently decreases detrital input to the basin. Instead, the marls of the Mariae Zone were most likely deposited during lowstand sea-level conditions, possibly enhanced by a global cooling period (Dromart *et al.*, 2003). The increased creation of accommodation space was most likely enhanced by high subsidence rates that affected the Vocontian Basin. The carbonate peak in the lower part of the Transversarium Zone (top of the S2 MS cycle) may thus record a major transgressive peak during a global warming period (e.g. Cecca *et al.*, 2005). Flooding of the Vocontian Basin would reduce detrital fluxes, and consequently enhance carbonate production.

Global sea-level variations are thought to be climatically and/or tectonically driven (e.g. Dromart *et al.*, 2003; Louis-Schmid *et al.*, 2007; Ramajo & Aurell, 2008). High-frequency sea-level fluctuations may have been orbitally forced by thermal oceanic water expansion (Gornitz *et al.*, 1982; Schulz & Schäfer-Neth, 1998) and/or changes in lake and groundwater storage (Jacobs & Sahagian, 1993; Hinnov & Park, 1999), or by glacio-eustasy (Frakes *et al.*, 1992; Dromart *et al.*, 2003). Nevertheless, variations of sea-level during this noted Jurassic greenhouse period need more investigation to better understand icehouse vs. greenhouse conditions.

CONCLUSIONS

High-resolution cyclostratigraphic analysis of MS was performed on three sections of the Terres Noires Formation at Aspres-sur-Buëch, Oze and Trescléoux, in the Vocontian Basin, SE France. The sections overlap the Early to Middle Oxfordian and are biostratigraphically constrained by an ammonite framework. Time-series analysis reveals the presence of a suite of significant sub-Milankovitch to Milankovitch frequencies. Long-term eccentricity components (405 kyr and $\sim$2 Myr) are recorded with the highest amplitudes. AM analysis highlights patterns consistent with those expected in the theoretical astronomical solution, and reinforce our orbital forcing hypothesis: the short eccentricity ($\sim$100 kyr) is modulated by the long-term eccentricity (405 kyr and $\sim$2 Myr). The $\sim$2 Myr periodicity, which corresponds to the $(g_4 - g_3)$ secular frequency term, is shorter than in Cenozoic times (i.e. $\sim$2.4 Myr). This difference in $(g_4 - g_3)$ could be related to the ancient chaotic motion of the Solar System.

The two prominent long-period cyclicities (i.e. 405 kyr and $\sim$2 Myr) were used to compare this composite section to sea-level depositional sequences proposed for the Oxfordian in previous studies. The 405 kyr cycles appear to have paced the third-order depositional sequences; the $\sim$2 Myr cycles, however, have no equivalents in the Mesozoic eustatic reference chart. This raises questions about the definition of the orders of depositional sequences in the chart.

The MS variations exhibit a decreasing long trend into the Middle Oxfordian (lower part of Transversarium Zone), associated with a progressive carbonate enrichment of the marls. The long-term carbonate evolution in the Terres Noires Formation is in excellent agreement with a gradual cooling period in the earliest Oxfordian (e.g. Dromart *et al.*, 2003), followed by a gradual warming in the Middle Oxfordian (Transversarium Zone) (e.g. Cecca *et al.*, 2005). This long-term trend reflects a major transgressive period, with lowstand conditions during the earliest Oxfordian within the Mariae Zone (maximum clay content), followed by a major transgression, peaking in the lower part of the Transversarium Zone (maximum carbonate content). Previously, opposing interpretations (transgression vs. regression) have been suggested for this interval (Jacquin *et al.*, 1998; Ramajo & Aurell, 2008).

Finally, the stable astronomical 405 kyr eccentricity cycle was used to calibrate the poorly constrained Oxfordian time scale of the Late Jurassic. The estimated duration of the composite Early–Middle Oxfordian astronomically forced sequence concurs with the current international Geological Time Scale, GTS2004 (3.8 ± 1.4 vs. 4.07 Myr). However, the estimated durations of ammonite zones within the substages differ notably from those in GTS2004.

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