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A new scenario for the Domerian - Toarcian transition

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Key words. – Upper Pliensbachian, Domerian, Toarcian, Anoxic event, Stratigraphic gap

Abstract. – In contrast to the majority of recently published hypotheses, we believe that the main trigger for early Toarcian anoxia is neither increased primary productivity during the Tenuicostatum and Falciferum Zones nor sudden methane hydrate degassing close to the transition between these two zones.

In our opinion, this peculiar paleoceanographic episode is linked to a major, though short-lived, regression at the end of Upper Domerian. Sea-level fall resulted from sudden cooling due to increased volcanic activity. This generated global thermal insulation and subsequent glaciation. The regression is responsible for a major hiatus over NW-European epicontinental seas and is later followed by the well-known Lower Toarcian transgression. The interval corresponding to this hiatus allowed vegetation to colonise vast newly emerged surfaces. The leaching and drowning of the accumulated organo-humic matter then triggered the anoxic cycle at the transgressive maximum, concomitant with a global warming.

Un nouveau scénario pour le passage Domérien - Toarcien

Mots clés. – Pliensbachien supérieur, Domérien, Toarcien, Anoxie, Lacune stratigraphique

Résumé. – Pour tenter de mieux comprendre l'événement d'anoxie océanique globale au Toarcien inférieur, il convient de remonter aux changements environnementaux qui ont précédé cette phase paroxysmale. En effet, la comparaison des séquences sédimentaires et biostratigraphiques du passage Domérien-Toarcien entre la Téthys occidentale (Maroc, Espagne, Portugal) et l'Europe du Nord-Ouest (Causses, Allemagne, Angleterre) fait apparaître une importante lacune dans la région septentrionale.

La faune d'Arieticeratinae (*Emaciaticeras*, *Canavaria, Fontanelliceras*) et d'Harpoceratinae (*Lioceratoides*, *Neolioceratoides*), accompagnée ensuite de *Dactylioceras* particuliers (groupe *mirabile-polymorphum* = sous-genre *Eodactylites*), fait presque totalement défaut en Europe du Nord-Ouest, alors qu'elle abonde dans les dernières alternances marno-calcaires, sans changement lithologique notable avec le Domérien des coupes téthysiennes. Cette faune est intercalée entre les derniers *Pleuroceras* et les *Dactylioceras* du groupe *tenuicostatum*. Ces derniers apparaissent dans les argiles succédant immédiatement au dernier banc calcaire à *Dactylioceras mirabile* au Portugal notamment. C'est là le diachronisme déjà reconnu entre les limites lithostratigraphique (disparition des bancs calcaires) et biostratigraphique (apparition du genre Dactylioceras) au passage Domérien-Toarcien.

Cette observation peut s'intégrer dans un nouveau scénario paléo-océanographique prenant en compte à la fois la tendance régressive majeure du Domérien supérieur (conduisant à une lacune régionale importante), l'abondance de matière charbonneuse dans les premiers dépôts transgressifs du Toarcien et l'événement anoxique global subséquent.

Dans la partie supérieure du Domérien, l'existence d'un fort volcanisme peut être déduite des données relatives aux variations des isotopes du strontium [McArthur *et al.*, 2000]. A ce pic de strontium sont associées une faible anomalie négative du δ^{13}C à la limite Domérien-Toarcien et des valeurs particulièrement élevées du δ^{18}O [Morettini et Bartolini, 1999]. Nous pensons que cette activité volcanique débute par des émissions massives de SO_2 induisant des pluies acides, un obscurcissement et un refroidissement. A cette phase de refroidissement correspond une augmentation de l'englacement des pôles et une régression responsable de la lacune majeure évoquée plus haut, particulièrement sensible dans les mers épicontinentales. Bien que les preuves directes d'une glaciation fini-domérienne fassent actuellement défaut [Hallam, 2001], le glacio-eustatisme nous semble le seul mécanisme permettant d'expliquer une oscillation marine importante mais de courte durée [Brandt, 1986 ; Dewey et Pitman, 1998]. En effet, le cycle régression-transgression s'étale sur environ deux zones d'ammonites, la lacune sédimentaire en elle-même recouvrant essentiellement les sous-zones à Elisa et Mirabile.

Ce premier épisode serait suivi, dans la zone à Tenuicostatum, par une importante perturbation du cycle du carbone responsable d'un effet de serre. Le réchauffement, provoquerait alors la transgression bien connue du Toarcien inférieur, cachetant le hiatus sédimentaire dans la province nord-ouest européenne. L'intervalle de temps correspondant à cette lacune aurait permis à la végétation de coloniser les immenses surfaces nouvellement émergées. C'est le lessivage et l'oxydation de la matière organo-humique et bactérienne accumulée pendant cette période, associée à une élévation de la température, qui aurait enclenché le mécanisme d'anoxie lors du paroxysme de la transgression.

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INTRODUCTION

The Lower Toarcian black shales are one of the best documented anoxic events in Phanerozoic times. They have been the focus of many different studies including paleoceanography, geochemistry and palaeontology [Jenkyns, 1988 ; Baudin *et al.*, 1990]. However, correlation problems remain [Jiménez *et al.*, 1996], as well as questions concerning their ultimate cause [Jenkyns, 1988 ; Wignall, 1994 ; Hesselbo *et al.*, 2000]. In order to better understand this major paleoceanographic disturbance, we have to take into account the environmental changes that occurred before the paroxysmic anoxic phase. Indeed, a comparison of sedimentary and biostratigraphic sequences at the Domerian-Toarcian transition in western Tethyan basins (Moroccan Middle-Atlas, Betic Cordillera, Lusitanian Basin) and NW-Europe (Causses Basin, Germany, British Isles) reveals a marked regressive phase in the Upper Domerian [Mouterde *et al.*, 1980 ; Brandt, 1986 ; Haq *et al.*, 1988 ; de Graciansky *et al.*, 1998 ; Wignall and Maynard, 1993], followed by an important hiatus in epicontinental Europe [Guex *et al.*, 2001]. In these regions, sedimentation resumes between the Semicelatum and Exaratum Subzones (respectively Upper Tenuicostatum and Lower Falciferum Zones) with abundant wood debris (Paris Basin [Mouterde *et al.*, 1980] ; Causses Basin : personal observations). Macroscopically visible carbonaceous matter is also known in Tethyan Lower Toarcian, preceding or associated with the organically rich levels marking the anoxic event (Madagascar [Bésairie, 1972] ; Betic Cordillera and Lusitanian Basin : personal observations).

These observations lead us to propose a new paleoceanographic scenario for the Upper Domerian - Lower Toarcian interval, that is discussed chronologically in this paper. A compilation of pertinent available geochemical data, such as strontium and carbon isotopic ratios, are summarised in figures 1 and 2. The biostratigraphic reference frame (fig. 2) also shows the position of the major hiatus discussed. Observations on the distribution of terrestrial organic debris (wood) within the Upper Domerian-Lower Toarcian interval are added, as well as relative paleotemperature variations deduced from $\delta^{18}O$ data.

UPPER DOMERIAN

A marked regressive trend is documented in Upper Domerian [Mouterde *et al.*, 1980 ; Brandt, 1986 ; Haq *et al.*, 1988 ; de Graciansky *et al.*, 1998 ; Wignall and Maynard, 1993]. In the Causses Basin (SE France), as well as in SW Germany, Domerian clays become more carbonated with abundant phosphatic concretions towards the top of the stage. These facies are characteristic of the less subsident parts of the basins [Mouterde *et al.*, 1980]. The regressive levels are dated from the Spinatum Zone, with the last *Amaltheidae* representatives and the sporadic appearance of *Emaciaticeras*, *Canavaria* and *Dactylioceras* of the *mirabile-polymorphum* group [Howarth, 1973 ;

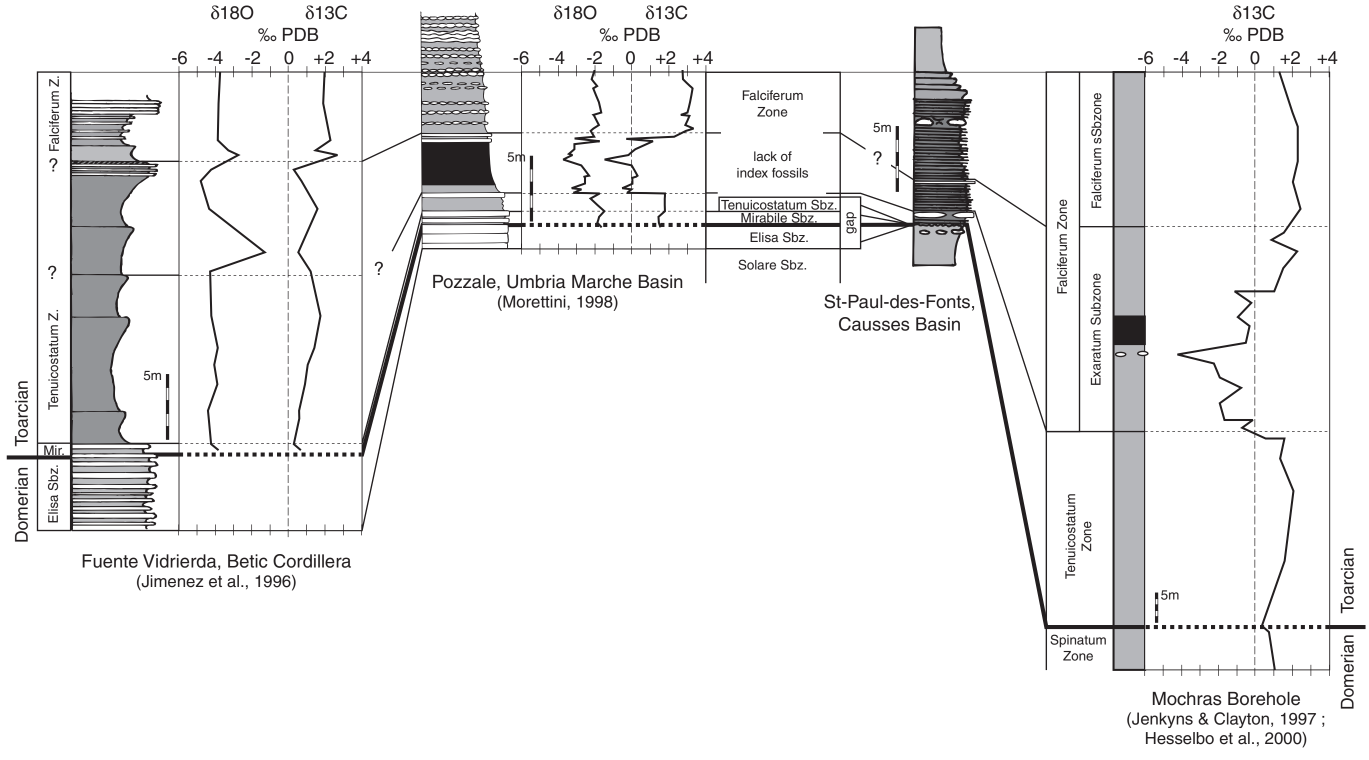

FIG. 1. – Representative Lower Toarcian sections with carbon and oxygen isotope curves from Tethys (Fuente Vidrierda [Jiménez *et al.*, 1996 ; personal observations], Pozzale [Morettini, 1998]) and NW-Europe (St-Paul-des-Fonts [personal observations], Mochras Borehole [Jenkyns and Clayton, 1997 ; Hesselbo *et al.*, 2000]). Only some of the localities, whose data were used for constructing figure 2, are shown.

FIG. 1. – *Colonnes stratigraphiques représentatives et courbes isotopiques du carbone et de l'oxygène pour le Toarcien inférieur de la Téthys (Fuente Vidrierda, Pozzale) et de l'Europe du Nord-Ouest (St-Paul-des-Fonts, Mochras Borehole).*

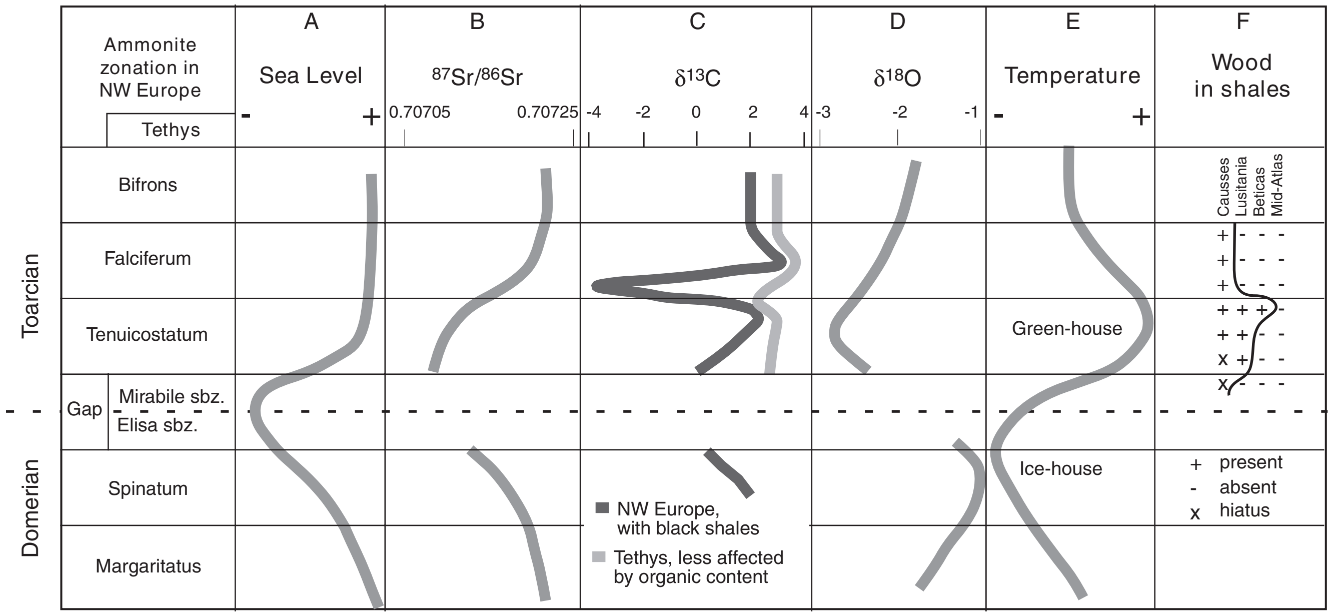

FIG. 2. – Simplified geochemical evolution across the Domerian-Toarcian boundary A) Sea level variation. B) Variations of the ^{87}Sr/^{86}Sr ratio [simplified from McArthur *et al.*, 2000]. C) δ^{13}C variation in NW Europe [Hesselbo *et al.*, 2000] and Umbria [Morettini, 1998 ; Morettini and Bartolini, 1999]. D) δ^{18}O variation [Morettini, 1998]. E) Variation of temperature (see text). F) Abundance of wood in shales (personal observations and compilation, see text for references).

FIG. 2. – *Évolution géochimique schématique au passage Domérien-Toarcien A) Variation du niveau marin. B) Variations du rapport ^{87}Sr/^{86}Sr [simplifié d'après McArthur et al., 2000]. C) Variation du rapport isotopique δ^{13}C pour l'Europe du Nord-Ouest [Hesselbo* et al., *2000] et l'Ombrie [Morettini, 1998 ; Morettini et Bartolini, 1999]. D) Variation du rapport isotopique δ^{18}O [Morettini, 1998]. E) Variation de la température. F) Abondance de débris charbonneux dans les argiles (observations personnelles et compilation, références dans le texte).*

Schlatter, 1982, 1985 ; Meister, 1989]. In Tethyan regions, Upper Domerian is commonly represented by marl-limestone alternations (fig. 1) with a diversification of Hildocerataceae species (*Lioceratoides, Canavaria, Emaciaticeras, Fontanelliceras*), and an abundant Dactylioceratidae fauna of the *mirabile-polymorphum* group (*Eodactylites* subgenus) within the last marl-limestone alternations, which are usually typical of Domerian sections in Tethyan regions. Although *Dactylioceras* seem to appear suddenly in Lowermost Toarcian, the oldest known representative is in fact an indeterminate species from the Middle Domerian of the Betic Cordillera [Braga, 1983], thus partly bridging the gap between this genus and its most probable ancestor : *Reynesoceras*.

In the upper part of the Domerian, strontium isotopic ratios may hint at increased volcanic activity (minimum of the ^{87}Sr/^{86}Sr ratio [McArthur *et al.*, 2000] and enhanced strontium abundance in whole rock analyses from Morocco and Spain, unpublished data). A faint δ^{13}C anomaly (fig. 1) and particularly high δ^{18}O values (bulk rock) are also associated with this Sr minimum close to the Domerian-Toarcian boundary [analytical details in Morettini, 1998 and Morettini and Bartolini, 1999]. We interpret all these elements as clues pointing to a global cooling event. Temperature drop is also evidenced by vegetation changes [Vakhrameev, 1991] and ammonite paleobiogeography [Macchioni and Cecca, 2002]. We suggest that this cooling event was due to thermal insulation following massive emission of SO_2 during the onset of volcanic activity in a still unknown geographic location (Karoo or Patagonia are possible candidates [Courtillot, 1995 ; Palfy and Smith, 2000 ; Wignall, 2001]). Polar glaciation and marine regression would be direct consequences of this cooling phase. Although no evidence of contemporaneous ice-caps are known at the moment [Hallam, 2001], glacio-eustatism seems the only reasonable mechanism to explain such short-term sea-level oscillations [Brandt, 1986 ; Dewey and Pitman, 1998]. The whole regression-transgression cycle approximately spans two ammonite zones, the sedimentary hiatus itself comprising most frequently two subzones (Elisa-Mirabile).

DOMERIAN – TOARCIAN TRANSITION

In the Causses region (S-France), the Upper Domerian regressive facies are capped with a red alteration level, which corresponds, in unaltered sections, to a thin pyritic bed. This pyrite was precipitated in marine anoxic conditions at the very beginning of the Toarcian transgression, due to the drowning and recycling of organic matter. A centimetric coal bed is locally associated with this level and is immediately overlain by "paper shales" intercalated by carbonated beds with *Dactylioceras semicelatum* (Upper Tenuicostatum Zone).

In England, *Pleuroceras* levels are shortly followed by nodular beds rich in *Dactylioceratidae* which define the base of the Tenuicostatum Zone (*D. clevelandicum* and *D. tenuicostatum*) [Howarth, 1973, 1980]. It should be stressed here that the Mediterranean *Dactylioceratidae* of the *mirabile-polymorphum* group (*Eodactylites* subgenus) are older than typical *tenuicostatum* group representatives (*Ortho-*

dactylites subgenus and *Dactylioceras s.s.*), as can be seen in Morrocco [Guex, 1973] and in the Lusitanian Basin [Elmi *et al.*, 1996]. This is proven by the sporadic co-occurrence of the Tethyan forms with *Pleuroceras spinatum* in NW-Europe [Howarth, 1973 ; Schlatter, 1982, 1985] and by their abundance at the very base of the Toarcian (Mirabile Subzone) together with *Lioceratoides* species, preceding or associated with *Protogrammoceras paltum* [Guex, 1973 ; Braga *et al.*, 1982 ; Elmi *et al.*, 1996 ; Macchioni, 2002].

Therefore, when correlating the Domerian-Toarcian transition levels on a large scale (fig. 1), one can readily observe that the interval between concretions with *Pleuroceras* (Spinatum Zone) and typical NW-European Lower Toarcian (Tenuicostatum Zone) covers a major stratigraphic gap corresponding to the Elisa and Mirabile Subzones in Iberia and Morocco, with a diversified *Emaciaticeras, Canavaria, Lioceratoides* and *Eodactylites* fauna. This sedimentary break is followed by the well-known Lower Toarcian transgression. Thus, there exists an obvious link between the anoxic paleoceanographic event recorded in Lower Toarcian beds and the preceding Upper Domerian major regression, associated with a large-scale stratigraphic gap.

The period corresponding to this hiatus, immediately after the Upper Domerian cooling stage and regression, enabled colonisation by vegetation to take place. Important CO_2 cycle perturbations, leading to a green-house effect and climate warming in the Tenuicostatum Zone, would have then produced a marine transgression leading ultimately to the recycling of huge quantities of organo-humic and bacterial matter, as will be discussed below.

LOWER TOARCIAN

When present, the Lower Toarcian deposits of NW Europe are dominated by the peculiar “Schistes-Cartons” or “Posidonien-Schiefer” facies. These organic-rich laminated marls range from the Upper Semicelatum Subzone (Upper Tenuicostatum Zone) to the end of the Falciferum Zone, or the base of the Bifrons Zone. Somewhat older levels are known from nodular beds in the British Isles and NW Germany (Lower Tenuicostatum Zone).

Current data on organic matter distribution and composition from Upper Domerian to Lowermost Toarcian, indicate a predominantly terrestrial input [Prauss and Riegel, 1989 ; Prauss *et al.*, 1991]. Conversely, it is well known that the organic matter from the Lower Toarcian black-shales (Upper Tenuicostatum-Lower Falciferum Zones) has a distinct marine signature [Baudin *et al.*, 1990]. However, such a marine signature does not exclude terrestrial influence. Terrestrial input is recorded by drifted wood, as well as spores and pollens occurring up to the Semicelatum and Exaratum Subzones.

The leaching and drowning of accumulated organo-humic matter, together with enhanced temperatures, triggered the anoxic mechanism by oxidation of organic carbon [Guex, 1999]. The large amounts of decaying organic matter could also lead to methane hydrate formation within the Tenuicostatum Zone. Degassing in a later phase (top of the Tenuicostatum Zone – base of the Falciferum Zone) would accentuate the negative $\delta^{13}C$ excursion and reinforce green-house conditions [Hesselbo *et al.*, 2000]. Increased primary productivity linked to upwelling [Jenkyns, 1988] does not seem necessary to generate the anoxic event, but may have occurred meanwhile. Finally, the $\delta^{13}C$ positive anomaly (figs. 1 and 2) following the negative peak discussed above would be easily explained by the final burial of light carbon stock.

CONSEQUENCES ON BIODIVERSITY ANALYSIS

A significant turnover of fauna occurred during the interval studied. The Upper Domerian is essentially marked by the disappearance of typical ammonites such as *Amaltheus* spp., *Pleuroceras* spp., *Pseudoamaltheus, Arieticeras, Becheiceras* and *Reynesoceras*. This major extinction event, due to the Upper Domerian regression, is followed by or concomitant to the radiation of a peculiar *Hildocerataceae* fauna (*Lioceratoides, Canavaria, Emaciaticeras, Fontanelliceras*) in meridional regions (Morocco, Italy, Spain, Portugal), prefigurative of the Toarcian representatives [Braga *et al.*, 1982]. The appearance of these new faunas is rapidly followed by the first occurrence of abundant *Dacytlioceratidae*, usually taken as diagnostic evidence for the base of the Toarcian. The representatives of both Upper Liassic families display large morphological variability, probably induced by some external environmental stress linked to the regressive episode (temperature change, marine pollution, possible acid rains). The reduction of carbonate production on epicontinental platforms [Dromart *et al.*, 1996] also hints at environmental stress. A second extinction event affecting benthic groups is documented at the top of the Tenuicostatum Zone in the NW-European province, and it is clearly linked to the anoxic event occurring at that time [Hallam, 1996 ; Macchioni and Cecca, 2002]. Therefore, it is important to distinguish between a first event leading to ammonite extinctions in NW-Europe, while diversification occurred in Tethys (Elisa-Mirabile Subzones), and a later benthos crisis due to anoxia (Upper Tenuicostatum and Falciferum Zones [Hallam, 1987 ; Harries and Little, 1999]). These events are differentially expressed both in terms of time and space [Macchioni and Cecca, 2002].

CONCLUSION

Our model can be briefly summarised as follows : a cooling event affected the Upper Domerian. This event was probably linked to large scale volcanic activity responsible for the expulsion/emission of large amounts of SO_2 leading to global thermal insulation (Karoo or Patagonia are potential sources [Courtillot, 1995 ; Palfy and Smith, 2000 ; Wignall, 2001]). It led to a glaciation/glacial period at the end of the Domerian and a concomitant major regression, recorded in NW-European Liassic sediments by an obvious shallowing sequence of facies [Mouterde *et al.*, 1980 ; Brandt, 1986 ; Haq *et al.*, 1988 ; de Graciansky *et al.*, 1998 ; Wignall and Maynard, 1993]. This regressive period finally resulted in a major hiatus encompassing the Domerian-Toarcian boundary [Guex *et al.*, 2001]. Huge forests developed on the newly emerged areas during that interval. Enormous amounts of organo-humic material were leached and drowned into the sea during the subsequent Lower Toarcian transgression, linked to climatic warming due to a green-house effect. This ultimately triggered the anoxic mechanism by oxidation of the organic carbon in the Upper Tenuicostatum Zone.

The Domerian-Toarcian transition is a rather complex and critical period on the mid-term. The expression of global paleoceanographic perturbations is clearly modulated by regional and local conditions (Tethys *vs*. NW-Europe, platform *vs*. basinal environments) and affects organisms differentially depending on their mode of life (necto-plankton *vs*. benthos). In our scenario, the Lower Toarcian anoxic event is the paroxysm of a crisis already beginning in the Upper Domerian and spanning a whole regression-transgression cycle.

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