Palaeogeography, Palaeoclimatology, Palaeoecology 441 (2016) 74–82

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Geochemical consequences of intense pulse-like degassing during the onset of the Central Atlantic Magmatic Province

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ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form 25 March 2015
Accepted 6 April 2015
Available online 18 April 2015

Keywords:
Central Atlantic Magmatic Province (CAMP)
Triassic–Jurassic Boundary (TJB)
Numerical modeling
GEOCLIM
Carbon system
Mass extinction

ABSTRACT

The Triassic–Jurassic boundary (TJB) is marked by one of the five largest mass extinctions of the Phanerozoic and the eruption of a large igneous province: the Central Atlantic Magmatic Province (CAMP). The TJB is characterized by a carbonate production crisis, by negative excursions in the carbon isotopic ratio of buried organic matter, and by successive peaks in atmospheric CO_2. Here we use the numerical model GEOCLIM to explore the possible connections between the CAMP emplacement and the observed carbon cycle perturbations. Different degassing scenarios linked to the CAMP eruption are explored. We show that the emission of realistic amounts of CO_2 that follow a geologically constrained degassing scenario as short-term peaks (less than 10 ka) leads to successive decrease in carbonate production, as observed in the geological record. We also calculate the evolution of carbon isotopes and show that our model reproduces the amplitude of the isotopic excursion with a volcanic degassing of CO_2 characterized by a carbon isotopic composition of −20‰. Such low values could be associated to carbon pools of light isotopic composition located at the transition zone [Cartigny, P. 2010, Earth and Planetary Science Letters, v. 296, p. 329–339] and not necessarily to biogenic methane release. Finally, the model predicts a succession of short-term CO_2 rises, with an amplitude in close agreement with available proxy-based reconstructions.

1. Introduction

The late Rhaetian is marked by one of the most important mass extinction of the Phanerozoic, in both the marine and terrestrial realms (Sepkoski, 1996; Hesselbo et al., 2007). The Triassic–Jurassic Boundary (TJB) crisis is coincident in time with the emplacement of the Central Atlantic Magmatic Province (CAMP), one of the largest Phanerozoic Large Igneous Provinces (LIP) in terms of area covered and volume of basalt emitted (Pálfy et al., 2001; McHone, 2002; Courtillot et al., 2003; Guex et al., 2004; Van de Schootbrugge et al., 2009; Blackburn et al., 2013; Dal Corso et al., 2014). The CAMP emplacement, similarly to other LIPs through the Mesozoic, affected the composition of the atmosphere through degassing of CO_2 and sulfur gases (McHone, 2002; Schaller et al., 2011; Richoz et al., 2012; Callegaro et al., 2014) and is thought to be the trigger of the TJB environmental crisis, even though bolide impact has also been suggested (Olsen et al., 2002).

From a geochemical point of view, the surficial Earth system appears to have been strongly disturbed at the TJB boundary. First, reconstructions of atmospheric CO_2 levels across the TJB based on paleosoil data from North America suggest the existence of 4, and possibly 5, ample peaks (Schaller et al., 2011, 2012). Those peaks might be the consequence of paroxysmal degassing episodes during the onset of the CAMP. Second, a major decrease in carbonate production is recorded at the TJB, together with a perturbation of the biological pump in the Tethys water column and possibly connected with ocean acidification (Kürschner et al., 2007; van de Schootbrugge et al., 2007, 2008; Clémence et al., 2010a, 2010b; Paris et al., 2010; Greene et al., 2012). Third, two negative carbon isotope excursions (CIE) in sedimentary organic carbon ($\delta^{13}C_{org}$) are recorded worldwide during the late Rhaetian and during the early Hettangian successively (Pálfy et al., 2001; Ward et al., 2001; Hesselbo et al., 2002; Guex et al., 2004; Galli et al., 2005; Kürschner et al., 2007; Ruhl et al., 2009; Whiteside et al., 2010; Bartolini et al., 2012; Meyer et al., 2013). The late Rhaetian CIE is also observed in carbonate carbon isotopic composition ($\delta^{13}C_{min}$) (Galli et al., 2005; Pálfy et al., 2007; Clémence et al., 2010b; Paris et al., 2010). However, in the section of St Audrie's bay (UK), the Hettangian excursion is

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http://dx.doi.org/10.1016/j.palaeo.2015.04.011
0031-0182/

recorded as a shift towards more negative $\delta^{13}C_{org}$ values and not as an actual excursion (Ruhl et al., 2010).

General circulation models and carbon cycle models are a powerful tool to reconstruct carbon cycle perturbation in the past. Huynh and Poulsen (2005) used a coupled ocean–atmosphere climate model to explore the consequence of an atmospheric CO_2 increase on the late Rhaetian climate. They concluded that the Earth system would have been deeply perturbed by an increase in atmospheric CO_2, with warm and dry summers affecting terrestrial ecosystems (Huynh and Poulsen, 2005). The consequences of a CO_2 degassing on the oceanic carbon chemistry have also been explored using the global carbon cycle model GEOCARB (Beerling and Berner, 2002; Berner and Beerling, 2007). These authors suggested that the late Rhaetian negative $\delta^{13}C$ excursion is due to clathrate dissociation and that the late Rhaetian carbonate production crisis was driven by the undersaturation of seawater with respect to calcite, as a result of the acidification promoted by the massive emissions of CO_2 and SO_2 from the CAMP (Beerling and Berner, 2002).

Here, we use the coupled climate–carbon cycle model GEOCLIM to explore the consequences of a geologically constrained scenario of CO_2 emissions from the CAMP (Fig. 1). Indeed, degassing of CO_2 from LIPs is usually modeled as a Gaussian distribution over the duration of the eruption. This assumption has been proven to be wrong, since the CAMP emplacement occurred as a succession of intense and short-lived pulses (Knight et al., 2004; Schaller et al., 2011). Concentrating the total release of CO_2 by the CAMP within a few peaks will impact the Earth system differently than assuming a continuous release. Release of CO_2 peak on timescales shorter than, or close to, the mixing time of the ocean–atmosphere system (~2–3 ka) forces the system out of steady state. The consequences of such short-lived CO_2 peaks on the late Triassic carbon cycle have never been explored before; which is the goal of this paper in the specific paleoenvironmental context of the TJB. We show in this work that a peak scenario allows the model to reproduce two of the global geochemical features of the TJB (evolution of the atmospheric CO_2 concentration and carbonate crisis), while the carbon isotope record requires a reconsideration of the mantle source carbon isotopic composition.

2. Model description

2.1. General description

GEOCLIM (Donnadieu et al., 2006a) couples the FOAM general circulation model (GCM) (Donnadieu et al., 2006b) to a model of the main biogeochemical cycles called COMBINE (Goddéris and Joachimski, 2004). The GCM is used to generate an offline grid of continental air temperature T_{air} and runoff R with a spatial resolution of 7.5°long × 4.5°lat. The atmospheric CO_2 concentrations used in the FOAM simulations range from 200 ppm up to 4200 ppm, with incremental steps every 200 ppm. At each time step, GEOCLIM calculates the atmospheric CO_2 concentration and the corresponding spatially distributed T_{air} and R above the continents through a linear interpolation procedure from the offline catalogue. For the purpose of the present study, we use a Rhaetian paleogeography (Donnadieu et al., 2006a).

The components of the biogeochemical cycles are calculated using a box model where the ocean is longitudinally divided into three parts, two polar oceans and one low- to mid-latitude ocean (Fig. 2). The polar oceans are located between −90° and −60° latitude for the southern hemisphere and +60° and +90° latitude for the northern hemisphere. Each polar ocean includes a photic zone and a deep ocean reservoir. The low- to mid-latitude ocean is divided vertically into three parts: the photic zone, the thermocline and the deep ocean

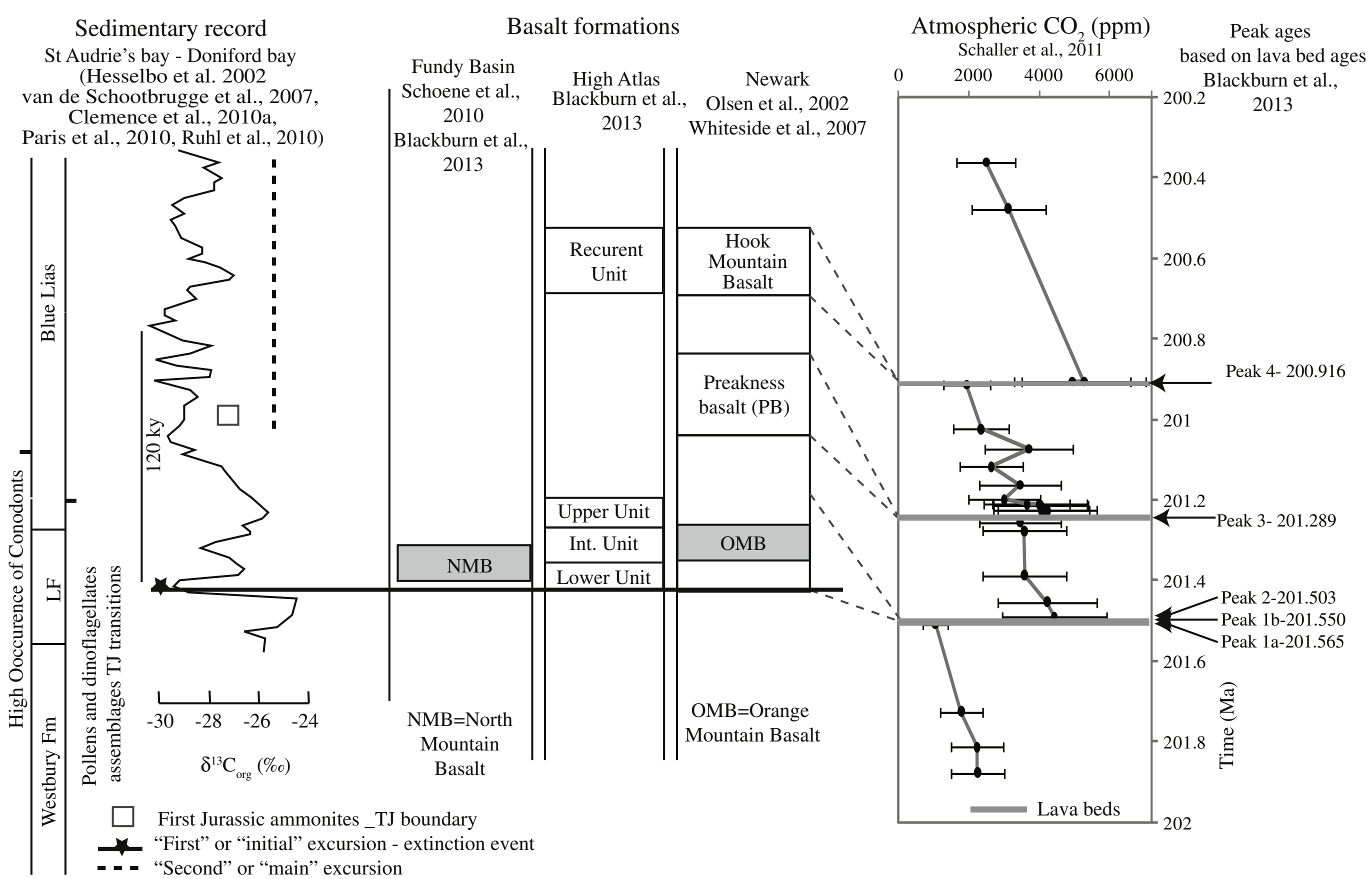

Fig. 1. Synchronicity between the late Rhaetian-early Hettangian sedimentary organic carbon isotopic composition negative excursion in UK, biological events around the TJB and CAMP volcanic events from North America and Morocco.