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Estimating the impact of the cryptic degassing of Large Igneous Provinces: A mid-Miocene case-study

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A B S T R A C T

Large Igneous Provinces (LIPs) have been emplaced throughout Earth's history, erupting great quantities ($>10^4$ km^3) of lava in long-lived ($>10^5$ y) events that have been linked to major environmental disruptions. The largest LIP eruptions (e.g. Siberian Traps) are widely considered to have had an impact on global climate through basalt CO_2 degassing but the impact of the more numerous smaller LIPs is debated. Here we test the hypothesis that LIPs had a greater impact on Earth's climate history than previously estimated because of the 'cryptic degassing' of intruded and crust-contaminated magma, injecting extra CO_2 over and above that coming from sub-aerial basalts. We use biogeochemical box models to investigate the potential impact of the Columbia River Basalts (CRB) during the mid-Miocene where multiple palaeorecords for this geologically relatively recent event enable more rigorous data-model comparison. We find that the effect on the long-term carbon cycle of basalt degassing from the CRB alone is negligible, but that a total CRB emission of 4090–5670 Pg of carbon with 3000–4000 Pg of this carbon emitted during the Grande Ronde Basalt eruptions, a flux within the acceptable estimated range when cryptic degassing is included, does well in reproducing the record of benthic $\delta^{13}C$ and atmospheric CO_2 change during the core of the Miocene Climatic Optimum. Nevertheless, mechanisms other than degassing are required to drive observed warmth before 16.3 Ma and to match observed calcite compensation depth behaviour after ∼15.4 Ma. Hence, our findings rule out the possibility that CRB emplacement alone can fully explain the mid-Miocene record but they demonstrate the enhanced climate impact that occurs when substantial cryptic degassing accompanies LIP emplacement.

1. Introduction

Large Igneous Provinces (LIPs) erupt great quantities of lava during long-lived events that can release significant volumes of carbon into the ocean–atmosphere system (Bryan and Ernst, 2008; Coffin and Eldholm, 1994; Courtillot and Renne, 2003; Ernst et al., 2005). While the LIPs with the largest volumes (e.g. the Siberian Traps or the Central Atlantic Magmatic Province) are widely accepted to have triggered episodes of carbon cycle perturbation, global warmth and ecological crisis (Grard et al., 2005; Sobolev et al., 2011; Wignall 2005, 2001), the case for LIPs with smaller ($\leq 2 \times 10^6$ km^3) volumes (e.g., the Deccan Traps or the Columbia River Basalt), emitting sufficient CO_2 to cause a significant global impact is a subject of debate (Caldeira and Rampino, 1990; Diester-Haass et al., 2009; Kender et al., 2009; Self et al., 2006; Taylor and Lasaga, 1999). However, estimates of LIP CO_2 emissions often do not take into account all of the potential sources of excess or 'cryptic' degassing, which include the often extensive volume of intrusive magma emplaced beneath LIPs (Grard et al., 2005; Karlstrom and Richards, 2011; Menand and Phillips, 2007; Shinohara, 2008), the metamorphic degassing of carbon-rich country rocks (Aarnes et al., 2011a; Erwin, 2006; Ganino and Arndt 2010, 2009; Iacono-Marziano et al., 2012; Retallack and Jahren, 2008; Svensen et al., 2009, 2004), and the potential impact of the recycling of mafic crust into the LIP magma source (Sobolev et al., 2011). These considerations imply that, under favourable circumstances, many LIPs may have a greater climatic impact than is widely accepted. Here we present the results of a feasibility study to quantify the potential additional impact on the long-term carbon cycle and climate of cryptic degassing using the mid-Miocene Columbia River Basalt (CRB) event for which multiple high-resolution palaeorecords are available.

2. The mid-Miocene and the Columbia River Basalt eruptions

Published composite records of benthic stable isotope and $CaCO_3$ accumulation presented in Fig. 1 indicate broadly contemporaneous anomalies (calcite compensation depth (CCD) shoaling,

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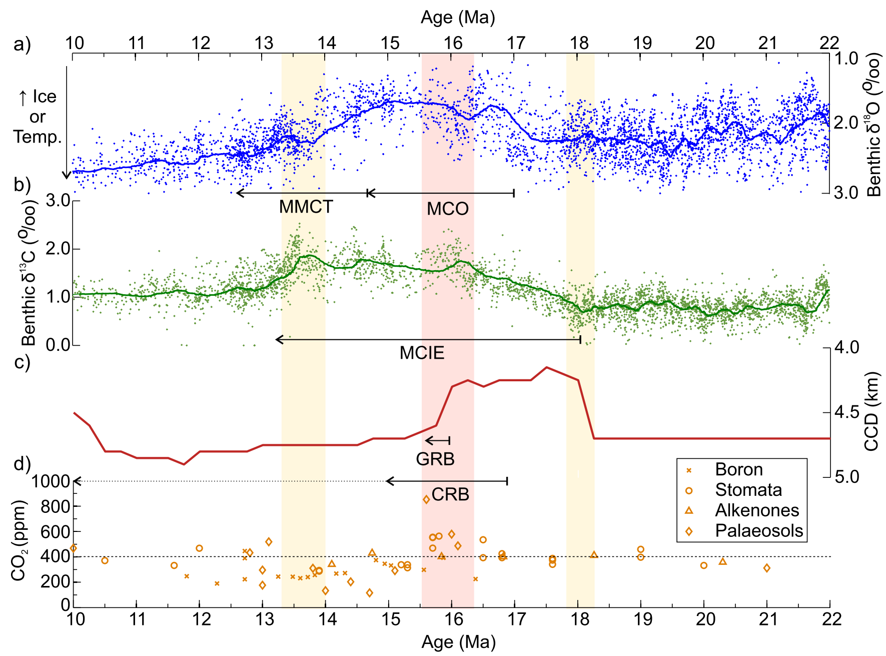

Fig. 1. Comparison of palaeorecords between 10 and 22 Ma of: benthic foraminifera a) $\delta^{13}C$ (black (green in the web version) dots) and b) $\delta^{18}O$ (black (blue in the web version) dots) compilations and their secular trends (solid black (blue/green in the web version) lines illustrate the 100-point moving average) (Zachos et al., 2008), c) equatorial Pacific CCD palaeodepth (solid black (red solid in the web version) line; Pälike et al., 2012), and d) atmospheric CO_2 reconstructed using boron (black (orange in the web version) crosses; Foster et al., 2012), alkenone (black (orange in the web version) triangles; Zhang et al., 2013), stomata and palaeosol (black (orange in the web version) circles and diamonds, respectively; Beerling and Royer, 2011) based techniques with the 400 ppm level marked by the dashed black line. The durations of the Miocene Climatic Optimum (MCO), mid-Miocene Climate Transition (MMCT), Monterey Carbon Isotope Excursion (MCIE), Columbia River Basalt (CRB) main eruption phase (with the minor Saddle Mountain eruptions shown by dotted arrow) and the Grande Ronde Basalt (GRB) eruptions are illustrated. Perturbations to the palaeorecords at ~18.0, ~16.0 and ~14.0 Ma are highlighted by the grey (orange and red in the web version) bars, with the dark grey (red in the web version) bar marking the perturbation which is the focus of this study and shown in greater detail in Fig. 3.

benthic $\delta^{13}C$ maximum, benthic $\delta^{18}O$ minimum, ice sheet extent minimum) in the long-term carbon cycle and climate system during the early to middle Miocene, including the Monterey Carbon Isotope Excursion (MCIE) and Miocene Climatic Optimum (MCO) (Billups and Schrag, 2003; Pälike et al., 2012; Passchier et al., 2011; Vincent and Berger, 1985; Zachos et al., 2008). These marked perturbations occurred at about the same time as the onset of the emplacement of the bulk of the CRB in the Cascadia region of North America over multiple eruption phases between ~16.8 and 15.0 Ma (Baksi, 2013; Barry et al., 2013, 2010; Hooper, 1997, 1988; Reidel et al., 2013b; Wolff and Ramos, 2013) (Fig. 2), with the initiation of the CRB eruptions coinciding with the core of both the MCO and the MCIE (Fig. 1). In detail, the peak of the carbon cycle perturbation occurs ca. 16.0 Ma (Fig. 3), coinciding with the eruption, between 16.3 and 15.9 Ma, of the ~152,000 km^3 Grande Ronde Basalt (GRB) formation over ~400 ky (responsible for ~70% of the CRB; Fig. 2; Barry et al., 2013; Reidel and Tolan, 2013; Reidel et al., 2013b; Wolff and Ramos, 2013). Using a Gaussian filter to remove signals below 420 ky in the benthic foraminifera $\delta^{13}C$ palaeorecord from ODP Site 1146 reveals a +0.3‰ excursion in the secular trend of benthic $\delta^{13}C$ between 16.3 and 15.8 Ma (Fig. 3, panel a) (Holbourn et al., 2007). Atmospheric CO_2 reconstructions feature elevated CO_2 during the MCO, perhaps peaking between 16.3 Ma and 15.8 Ma at 400–500 ppmv despite evidence of increased organic carbon burial during the Monterey Excursion, and then declining by ~13.9 Ma (Fig. 3, panel c) (Foster et al., 2012; Kürschner et al., 2008; Vincent and Berger, 1985; Zhang et al., 2013). The CCD also deepens by ~300 m in the equatorial Pacific at ~16.0 Ma, which has been suggested to represent a recovery from an equatorial "carbonate famine" hypothesised to have caused the CCD to initially shoal at ~18.0 Ma (Fig. 1; Fig. 3, panel b) (Lyle, 2003; Lyle et al., 2010; Pälike et al., 2012). These correlations have led some authors to invoke CRB activity as the main driver of mid-Miocene climate change (e.g. Hodell and Woodruff, 1994; Kender et al., 2009; Foster et al., 2012). Others have concluded that CRB emissions had a negligible impact on atmospheric CO_2 (Taylor and Lasaga, 1999; Diester-Haass et al., 2009).

To investigate the potential importance for Miocene climate of CRB cryptic degassing we use model simulations to determine the magnitude and duration of carbon emissions necessary to reproduce the observed patterns in benthic $\delta^{13}C$, the CCD and atmospheric CO_2 and evaluate the feasibility of these emission scenarios against the range of potential emissions calculated for the CRB.

3. Materials and methods

3.1. Modelling

We use two biogeochemical box models to simulate the carbon emissions necessary to drive the changes seen in the palaeorecord: i) the model of Merico et al. (2008) (hereafter referred to as MTW08), and ii) the LOSCAR model (Zeebe et al., 2009). MTW08 is an open system model containing all the major fluxes and processes in the carbon, phosphorus and silica cycles, including the carbonate system, air–sea gas exchange, the organic matter pump, CO_2 draw down by silicate weathering, calcium carbonate formation and cycling and carbon isotopes (Merico et al., 2008). In contrast, LOSCAR (the Long-term Ocean–atmosphere–Sediment CArbon cycle Reservoir model) includes a simplified phosphorous cycle and no silica cycle but includes a sediment component coupled to the ocean–atmosphere routines, allowing the carbonate system to be better represented by including dissolution processes within the sediment column (Zeebe, 2012; Zeebe et al., 2009). LOSCAR also includes regional boxes for each ocean basin in contrast to the global ocean of MTW08, providing a better comparison to the Pacific-focused palaeorecords used in this study. Both models are limited by low spatial resolution, uncertainties in mid-Miocene