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Atmospheric methane from organic carbon mobilization in sedimentary basins — The sleeping giant?

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ABSTRACT

The mass of organic carbon in sedimentary basins amounts to a staggering 10^{16} t, dwarfing the mass contained in coal, oil, gas and all living systems by ten thousand-fold. The evolution of this giant mass during subsidence and uplift, via chemical, physical and biological processes, not only controls fossil energy resource occurrence worldwide, but also has the capacity for driving global climate: only a tiny change in the degree of leakage, particularly if focused through the hydrate cycle, can result in globally significant greenhouse gas emissions. To date, neither climate models nor atmospheric CO_2 budget estimates have quantitatively included methane from thermal or microbial cracking of sedimentary organic matter deep in sedimentary basins. Recent estimates of average low latitude Eocene surface temperatures beyond 30 °C require extreme levels of atmospheric CO_2. Methane degassing from sedimentary basins may be a mechanism to explain increases of atmospheric CO_2 to values as much as 20 times higher than pre-industrial values. Increased natural gas emission could have been set in motion either by global tectonic processes such as pulses of activity in the global alpine fold belt, leading to increased basin subsidence and maturation rates in the prolific Jurassic and Cretaceous organic-rich sediments, or by increased magmatic activity such as observed in the northern Atlantic around the Paleocene–Eocene boundary. Increased natural gas emission would have led to global warming that was accentuated by long lasting positive feedback effects through temperature transfer from the surface into sedimentary basins. Massive gas hydrate dissociation may have been an additional positive feedback factor during hyperthermals superimposed on long term warming, such as the Paleocene–Eocene Thermal Maximum (PETM). As geologic sources may have contributed over one third of global atmospheric methane in pre-industrial time, variability in methane flux from sedimentary basins may have driven global climate not only at time scales of millions of years, but also over geologically short periods of time. Earth system models linking atmospheric, ocean and earth surface processes at different timescales with the sedimentary organic carbon cycle are the tools that need to be developed in order to investigate the role of methane from sedimentary basins in earth's climate.

Contents

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1. Introduction

Atmospheric CO_2 levels are an expression and a driving factor of earth's climate. The same is true for methane levels that contribute about 15% of the total 2.5 W/m^2 increase in radiative forcing from the anthropogenic release of greenhouse gasses in the industrial age (Hansen and Sato, 2001; Chen and Prinn, 2006). Between 1960 and 1999, methane concentrations grew on average six times faster than over any 40-year period of the two millennia before 1800, despite a near-zero growth rate since 1980 (Denman et al., 2007). The current rapid increase of atmospheric CO_2 related to human activity represents an extreme situation in earth's history but is not unique, in the past 65 Myrs of earth's evolution (Zachos et al., 2008). In fact, carbon release during the past 50 years from anthropogenic sources is of a similar order of magnitude as it was during the onset of the Paleocene Eocene Thermal Maximum (PETM) 55 Million years ago (Zeebe et al., 2009). Dramatic $\delta^{13}C$ and $\delta^{18}O$ excursions during this event have been attributed to catastrophic methane release from gas hydrates (Kennett and Stott, 1991; Dickens et al., 1995; Thomas et al., 2002). Alternatively, increased mobilization of sedimentary organic matter by volcanic intrusions (Svensen et al., 2004), augmented by organic carbon oxidation related to surficial processes, such as wildfires and modified ocean circulation, has been proposed (Kurtz et al., 2003; Higgins and Schrag, 2006). Recent recalibrations of sea surface temperatures show that ocean surface temperatures in the Eocene may have been up to 10 °C higher than previously thought (Pearson et al., 2001; Sexton et al., 2006; Bijl et al., 2009; Hollis et al., 2009). This suggests that hyperthermals were occurring when average tropical ocean surface temperatures were already above or close to 30 °C, implying average temperatures beyond 35 °C (Huber, 2008). If we accept that carbon greenhouse gasses are the main driving factor in global warming (Crowley, 2000), this also implies that carbon content of the atmosphere in the past was many times higher than today. During the initial PETM warming event up to 3000 Gt of carbon were released to the surface (Zeebe et al., 2009) and between 4480 and 6800 Gt during the entire PETM event (Panchuk et al., 2008; Zeebe et al., 2009). This estimate is constrained by the magnitude of the $\delta^{13}C$ excursion and the rise of the Carbonate Compensation Depth (CCD) in response to increased CO_2 uptake by the oceans. Depending on the changing sensitivity of the effective radiative forcing to surface carbon inventory changes (Goodwin et al., 2009), the amount of carbon released to the surface may not have been enough to explain the observed warming by increase in atmospheric CO_2 alone (Zeebe et al., 2009). Additional warming may have been caused by initial release to the atmosphere as methane, which is a much stronger greenhouse gas than CO_2 (Sloan et al., 1992; Khalil and Rasmussen, 1995; Zeebe et al., 2009). While individual or a combination of several sudden methane release mechanisms may explain a geologically short $\delta^{13}C$ excursion, such as at the PETM, much higher amounts of released carbon are necessary to sustain CO_2 concentrations for longer periods (Pagani et al., 2006). This is especially true for the Early Eocene, when, after $\delta^{13}C$ values had approximately returned to pre-PETM levels, $\delta^{13}C$ values again decreased almost to PETM level in the course of several Myrs (Cramer et al., 2003; Nicolo et al., 2007; Galeotti et al., 2010). Such a continuous or pulsed release of additional organic carbon to the surface is difficult to explain quantitatively by the mechanisms proposed to date (Pagani et al., 2006).

A comprehensive climate model has to not only take into account all aspects and potential feedbacks of atmosphere–ocean–biosphere interaction (e.g. Cox et al., 2000; Falkowski et al., 2000), but must also include the entire lithospheric part of the cycle (Fig. 1). Existing models that quantitatively simulate atmosphere–lithosphere interaction on a global scale take into account factors such as solar radiation, silicate weathering and atmosphere–biosphere interaction but not thermal and biogenic remobilization of buried organic carbon (e.g., Caldeira and Kasting, 1992; Tajika, 1998; Franck et al., 1999; Hansen and Wallmann, 2003; Bergmann, et al., 2004; Berner, 2006; Beerling et al., 2009). Recent numerical earth system models partially include sedimentation and remobilization of organic carbon, but not deep burial and thermal cracking (e.g. Brovkin et al., 2007; Shaffer et al., 2008). Once buried, the sedimentary organic carbon reservoir is generally thought to be a relatively stable and largely immobile part of the global carbon cycle. However, this gigantic carbon reservoir might be much more dynamic than commonly realized. Considering that only a tiny fraction (0.1%) of the 15×10^{21} g of organic carbon are cycling in active surface pools (Berner, 1989; Hedges and Keil, 1995), small variations in the interaction with the deep carbon reservoir will have a considerable impact on surface processes. Evidence of the connection between deep reservoirs of