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Modelling hydrothermal venting in volcanic sedimentary basins: Impact on hydrocarbon maturation and paleoclimate

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ABSTRACT

Vent structures are intimately associated with sill intrusions in sedimentary basins globally and are thought to have been formed contemporaneously due to overpressure generated by gas generation during thermogenic breakdown of kerogen or boiling of water. Methane and other gases generated during this process may have driven catastrophic climate change in the geological past. In this study, we present a 2D FEM/FVM model that accounts for 'explosive' vent formation by fracturing of the host rock based on a case study in the Harstad Basin, offshore Norway. Overpressure generated by gas release during kerogen breakdown in the sill thermal aureole causes fracture formation. Fluid focusing and overpressure migration towards the sill tips results in vent formation after only few tens of years. The size of the vent depends on the region of overpressure accessed by the sill tip. Overpressure migration occurs in self-propagating waves before dissipating at the surface. The amount of methane generated in the system depends on TOC content and also on the type of kerogen present in the host rock. Generated methane moves with the fluids and vents at the surface through a single, large vent structure at the main sill tip matching first-order observations. Violent degassing takes place within the first couple of hundred years and occurs in bursts corresponding to the timing of overpressure waves. The amount of methane vented through a single vent is only a fraction (between 5 and 16%) of the methane generated at depth. Upscaling to the Vøring and Møre Basins, which are a part of the North Atlantic Igneous Province, and using realistic host rock carbon content and kerogen values results in a smaller amount of methane vented than previously estimated for the PETM. Our study, therefore, suggests that the negative carbon isotope excursion (CIE) observed in the fossil record could not have been caused by intrusions within the Vøring and Møre Basins alone and that a contribution from other regions in the NAIP is also required to drive catastrophic climate change.

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1. Introduction

Hydrothermal vent complexes are closely linked to igneous sheet intrusions in sedimentary basins where they form conduits for the release of fluids and gases generated in metamorphic aureoles. The vent complexes form pipe-like lower conduit structures, commonly observed to originate from near the tips of sills or other topological highs related to sill morphology, along with an upper part which manifests itself as a crater or dome at the paleosurface. Examples of this association have been observed globally and include the Vøring and Møre basins in the Norwegian Sea (Jamtveit et al., 2004; Planke et al., 2005; Svensen et al., 2004), the Karoo Basin in South Africa (Svensen et al., 2006), the Faroe–Shetland Basin (Grove, 2013; Hansen, 2006) and the Tunguska Basin in Siberia (Svensen et al., 2009). Extensive sill complexes are characteristic of Large Igneous Provinces (LIPs) emplaced in sedimentary basins, and considerably modify the thermal and hydrological properties of the host sedimentary strata. The understanding of this process is of importance not only to the scientific community but also to the industry as it can significantly affect petroleum exploration in volcanic basins (Monreal et al., 2009).

Two main overpressure mechanisms have been proposed to explain the formation of sill-associated hydrothermal vent com-

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plexes. The first mechanism suggests that boiling of pore fluid within the thermal aureole of the intruding sill and the release of additional fluids during metamorphic dehydration reactions would result in a large volume increase, thereby increasing the fluid pressure (Jamtveit et al., 2004). Hydrofracturing occurs once the fluid pressure exceeds the lithostatic and results in the formation of a vent. However, this mechanism would be limited to the upper 1 km of the sedimentary basin where pressures allow for the boiling of pore fluids. The second mechanism suggests that fluid overpressure may be generated by the release of various gases such as CO_2, SO_2 and halocarbons during metamorphic dehydration reactions (Aarnes et al., 2010). Generation of large quantities of gaseous hydrocarbons such as CH_4 could result in large overpressures triggering catastrophic blowouts (Aarnes et al., 2012).

In a previous study, Iyer et al. (2013) developed a numerical model for a single generic sill that generated hydrothermal plumes without any need for overpressure mechanisms. These vents develop within few hundred years after sill emplacement and are controlled by flow patterns around the cooling intrusion. However, vent formation in this model is restricted to relatively high permeability systems. In this paper, we build on the model presented by Iyer et al. (2013) and study vent formation due to hydrofracturing associated with sill intrusives in low permeability systems. The study is based on a 2D transect in the Harstad Basin, offshore Norway, where multiple sills have been imaged in association with one main hydrothermal vent complex observed above the tip of the main sill. The model aims to recreate the observed vent structure and tracks the amount of thermogenic methane released into the system. Using this, we evaluate the amount of methane that vents from a single vent and extrapolate this volume up to the basin scale and reinvestigate its link to catastrophic extinction events.

2. Geological setting

The Harstad Basin is located on the Norwegian continental shelf in the SW part of the Barents Sea, along the transition from the rifted Lofoten–Vesterålen margin to the sheared W Barents Sea margin (Fig. 1a). It is bounded to the west by the continent-ocean boundary and to the east by the southernmost extension of the Troms–Finnmark Fault system (Olesen et al., 2002). The basin comprises a narrow rift basin forming a northerly extension of the NE Atlantic late Middle Jurassic-earliest Cretaceous rift system which formed the major depocentres of the Vøring and Møre basins further south (Faleide et al., 2008). Minor magmatism occurred in the Harstad Basin during the Paleogene continental breakup between Norway and Greenland. To date, only one exploration well (7016/2-1) has been drilled into the far north of the basin making it a largely untested frontier basin. Well 7119/12-3, located ca. 100 km NE of the study area within the Ringvassøy–Loppa Fault Complex, was identified as the most suitable tie well outside the basin.

A seismic-stratigraphic interpretation of key horizons in the Harstad Basin is presented in Fig. 1 and is based on interpretation of regional 2D and 3D seismic data and borehole ties. The basin has over 8 km of accumulated sediment in the deepest part and is dominated by a thick Lower Cretaceous succession. A number of laterally extensive sheet intrusions have been identified and mapped within the study area. Intrusions were identified by a combination of high amplitude, transgressive sections, saucer-shaped morphologies and associated hydrothermal vent complexes (Planke et al., 2005, 2014). The main sill body within the study area extends over ca. 380 km^2 in plane view and displays an elongated saucer-shaped morphology. An average thickness of ca. 0.1 km is inferred for the main sill based on interpretation of pre- and post-stack seismic reflection data (Planke et al., 2014), giving a total volume of ca. 4 km^3 for the main sill complex.

A well-defined hydrothermal vent complex is imaged above the sill tip in the central part of the study area (Fig. 1b). The vent is characterized by a ca. 1.5 km wide mound-shaped structure above the Base Vent horizon, interpreted to be the paleo-seafloor at the time of venting. Disturbed reflections within a narrow region between the sill tip and the mound represent the lower conduit zone (Planke et al., 2005) surrounded locally by inward dipping and layer-parallel high-amplitude. The high-amplitude events are interpreted as gas-charged sediments. The age of the venting is interpreted to be of earliest Eocene age (ca. 55.8 Ma), similar to the age of similar hydrothermal vent complexes mapped in the Vøring Basin (Svensen et al., 2010, 2004).

3. Mathematical model

The 2D hybrid FEM/FVM model (Finite Element Method/Finite Volume Method) presented here builds on the model presented by Iyer et al. (2013).

3.1. Hydrothermal convection

The fluid density changes are spilt into the pressure and temperature equivalents to give the pressure field for a compressible fluid (Eqn. (1)). The pressure equation also accounts for the source term associated with methane generated by thermal cracking of organic matter (see section 3.2). Fluid properties are based on pure water corresponding to the IAPWS-84 steam tables (http://www.iapws.org/).

$$\phi\rho_f\beta_f\frac{\partial P}{\partial t} = \nabla\left[\frac{k\rho_f}{\mu_f}(\nabla P - \rho_f\vec{g})\right] - \rho_f\frac{\partial\phi}{\partial t} + \phi\rho_f\alpha_f\frac{\partial T}{\partial t} + R_{CH_4} \tag{1}$$

Table 1 lists all the notations and values used in the model.

The energy equation (Eqn. (2)) describes diffusive and advective heat transfer including radioactive heat production in the sediments.

$$\left[\phi\rho_f c_{pf} + (1-\phi)\rho_r c_{peff}\right]\frac{\partial T}{\partial t} = -\rho_f c_{pf}\vec{v_f}\cdot\nabla T + \nabla\cdot(\kappa\nabla T) + \lambda \tag{2}$$

3.2. Thermal maturation and methane generation

We use two different methods to calculate the amount of methane generated during thermogenic breakdown of organic material in sediments. The previously used, first method is generic and is based on a simple conversion of thermal maturity to methane generation (Aarnes et al., 2010; Iyer et al., 2013). Except for TOC content, this method does not account for any other sediment property and assumes a maximum of 85% TOC conversion to hydrocarbons. The second, more robust method is widely used within the petroleum industry to determine hydrocarbon generation and is based on the organofacies concept (Pepper and Corvi, 1995a, 1995b; Pepper and Dodd, 1995). This method takes the depositional environment of the sedimentary layer into account and accordingly categorizes the kerogen that constitutes TOC available for hydrocarbon generation.

3.2.1. Generic method

Vitrinite reflectance is a widely used indicator of thermal maturity and can be readily measured in the field. One of the most common methods used to calculate the synthetic thermal maturity of the source rock is the EASY%Ro method put forward

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