Earth and Planetary Science Letters 467 (2017) 72–78

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Hydrothermal vent complexes offshore Northeast Greenland: A potential role in driving the PETM

P. Reynolds[a,b,*], S. Planke[b,c], J.M. Millett[b,e], D.A. Jerram[c,d], M. Trulsvik[b], N. Schofield[e], R. Myklebust[f]

[a] Centre for Tectonics, Resources and Exploration (TRaX), Australian School of Petroleum, University of Adelaide, Adelaide, SA 5005, Australia
[b] Volcanic Basin Petroleum Research (VBPR), Oslo Science Park, Norway
[c] Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway
[d] DougalEARTH Ltd., Solihull, UK
[e] Department of Geology and Petroleum Geology, University of Aberdeen, UK
[f] TGS, Lensmannslia 4, 1386 Asker, Norway

ARTICLE INFO

Article history:
Received 1 November 2016
Received in revised form 23 March 2017
Accepted 24 March 2017
Available online xxxx
Editor: T.A. Mather

Keywords:
hydrothermal vent complexes
sill intrusions
PETM
global climate change
Greenland
NAIP

ABSTRACT

Continental rifting is often associated with voluminous magmatism and perturbations in the Earth's climate. In this study, we use 2D seismic data from the northeast Greenland margin to document two Paleogene-aged sill complexes $\geq$18 000 and $\geq$10 000 km^2 in size. Intrusion of the sills resulted in the contact metamorphism of carbon-rich shales, producing thermogenic methane which was released via 52 newly discovered hydrothermal vent complexes, some of which reach up to 11 km in diameter. Mass balance calculations indicate that the volume of methane produced by these intrusive complexes is comparable to that required to have caused the negative δ^{13}C isotope excursion associated with the PETM. Combined with data from the conjugate Norwegian margin, our study provides evidence for margin-scale, volcanically-induced greenhouse gas release during the late Paleocene/early Eocene. Given the abundance of similar-aged sill complexes in Upper Paleozoic–Mesozoic and Cretaceous–Tertiary basins elsewhere along the northeast Atlantic continental margin, our findings support a major role for volcanism in driving global climate change.

1. Introduction

Volcanic rifted margins are associated with voluminous extrusive and intrusive igneous activity (Menzies et al., 2002; Jerram and Widdowson, 2005) of which the northeast Atlantic margins are type examples (e.g. Saunders et al., 1997). Here, extrusive activity during the Paleocene and Eocene produced characteristic Seaward Dipping Reflectors and extensive subaerial lava flows, whilst intrusive activity produced igneous centres (Jerram and Bryan, 2015) and sill complexes $\geq$80 000 km^2 in size (Planke et al., 2005; Schofield et al., 2015).

The emplacement of sill complexes can generate huge quantities of greenhouse gases by metamorphic reactions within the intrusion aureole system (e.g. Aarnes et al., 2011, 2012, 2015). The composition and volumes of gases generated are dependent on a range of factors including (and most importantly) host rock composition, total organic content (TOC) and permeability; in addition to intrusion volume, temperature and emplacement depth (Aarnes et al., 2012; Iyer et al., 2013). A proportion of these gases are released to the atmosphere or hydrosphere through hydrothermal vent complexes within tens of years of sill intrusion (e.g. Jamtveit et al., 2004; Aarnes et al., 2010). Hydrothermal vent complexes commonly form above sill tip terminations as a result of intensive fracturing or brecciation of overburden strata in the shallow subsurface. These overburden breaches are caused by overpressure build up associated with the boiling of pore fluids and host rock devolatilization reactions (Jamtveit et al., 2004; Aarnes et al., 2012). Where vent structures are observed in seismic data, they have eye, dome or crater-like upper parts (Planke et al., 2005; Møller Hansen, 2006). The lower parts are characterised by a central pipe, commonly surrounded by a region of inwardly dipping strata that is contained within metamorphosed sedimentary rocks (Møller Hansen, 2006; Svensen et al., 2007). Release of gases from these vents is thought to have played a primary role in driving global warming, as proposed for the Paleocene Eocene Thermal Maximum (PETM) (Svensen et al., 2004).

Extensive sill complexes are documented from the United Kingdom Continental Shelf (e.g. Schofield et al., 2015) and the Nor-

* Corresponding author.
E-mail address: peter.reynolds@adelaide.edu.au (P. Reynolds).

http://dx.doi.org/10.1016/j.epsl.2017.03.031

wegian margin (Svensen et al., 2004) where hydrothermal vent complexes are also recognised. Whilst onshore studies have documented sills within Carboniferous–Cretaceous-aged sediments (Price et al., 1997; Therkelsen, 2016), sparse data coverage in regions covered by sea ice and poor seismic imaging beneath the "top basalt" reflection means that the offshore section of this margin has long been a significant gap in our understanding of the northeast Atlantic continental margins. Without the full extent of intrusive complexes in the North Atlantic Igneous Province (NAIP) being recognised and mapped, the role of margin-scale intrusive volcanic activity in driving global climate change has remained uncertain.

This study uses newly acquired 2D seismic data to document the distribution and architecture of sill complexes and associated hydrothermal vent complexes along the offshore northeast Greenland margin. A combination of seismic mapping, field evidence (e.g. Larsen and Marcussen, 1992) and burial history curves (Mathiesen et al., 2000) indicate that the sills within the Danmarkshavn Basin regionally intruded Jurassic-aged, shale-rich horizons at paleodepths of >3 km, whilst in the Thetis Basin they intruded Cretaceous-aged host rocks at paleodepths of 1–2 km. The Jurassic-aged shales have TOC (total organic carbon) contents up to twenty times higher than those reported from the Norwegian margin (Svensen et al., 2004; Price and Whitham, 1997). Contact metamorphism of these shales resulted in the voluminous production of greenhouse gases such as methane, released into to the atmosphere via hydrothermal vent complexes (Svensen et al., 2004; Aarnes et al., 2015). Combined with data from the Norwegian and United Kingdom Continental Shelf margins, we show that volcanically-induced greenhouse gases were produced on a scale capable of producing the observed negative δ^{13}C excursion during the PETM.

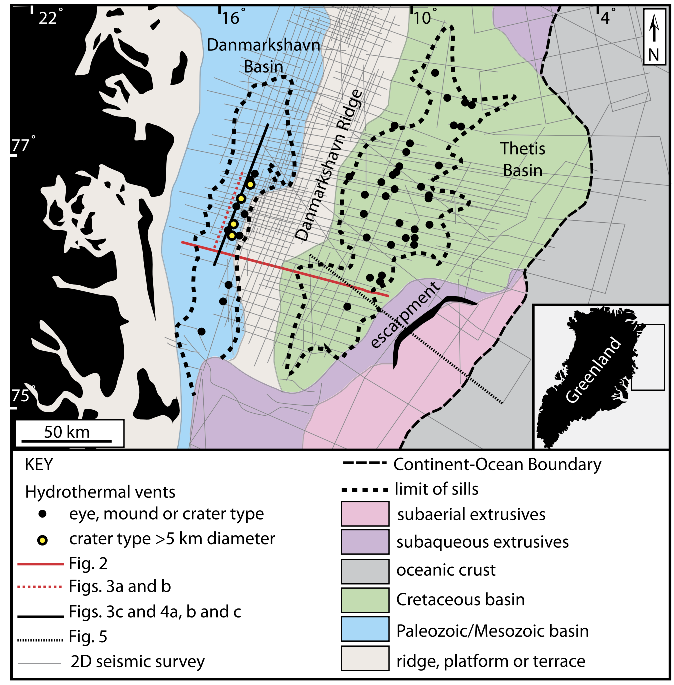

Fig. 1. Map showing the Danmarkshavn and Thetis Basins and the distribution of volcanic units. Inset shows the location of the study area along the Greenland coast. Adapted from Hamann et al. (2005).

2. Dataset and methods

This study utilizes 2D seismic profiles acquired by TGS in 2008–2009 and 2011–2014, including re-processed AWI data. The surveys cover an area of ~125 000 km^2, with the lines ranging from 40–250 km in length and spacings varying from 0.1–40 km. Seismic interpretation was conducted using Kingdom software. The extrusive and intrusive volcanic facies have been mapped on intersecting 2D seismic lines (Fig. 1) using the seismic volcanostratigraphic methods of Planke et al. (2000, 2015). In the absence of well data we use a p-wave velocity of 5.5 km s^{-1} to determine the resolution and detection limit for the sills (Skogly, 1998; Berndt et al., 2000) and a velocity of 1.8 km s^{-1} to calculate the dimensions of the upper parts of the vents (Planke et al., 2005). The sedimentary basins are correlated with the onshore successions of east and northeastern Greenland, and offshore successions in the southern Barents Sea and on the mid-Norwegian shelf (Hamann et al., 2005; Tsikalas et al., 2005). More than one hundred gravity core and tens of dredges have been acquired to study hydrocarbon seepages and to allow seismostratigraphic ties.

3. Interpretation of sill and hydrothermal vent complexes

The sills are characterised by high amplitude, positive reflections, indicating a significant downwards increase in acoustic impedance. They commonly display abrupt terminations, saucer shaped morphologies and transgress the stratigraphy (Figs. 2 and 3); diagnostic features of igneous intrusions (e.g. Planke et al., 2005, 2015). The sills are dominantly found within two complexes; a ≥18 000 km^2 complex in the Cretaceous–Tertiary age Thetis Basin and a ≥10 000 km^2 complex in the Upper Paleozoic–Mesozoic-aged Danmarkshavn Basin. The sills within these complexes are also documented by Hamann et al. (2005) and Geissler et al. (2016). The sill complexes follow the structural trend of the basins and are oriented NNE/SSW (Fig. 1). Within the Thetis Basin the sills are up to 28 km in diameter and were emplaced at depths of 1–2 km; this is interpreted from their relationship to the Vent Horizon (see below). In the Danmarkshavn Basin the sills are up to 40 km in diameter and were emplaced at depths of 3–5 km. The sills in the Danmarkshavn Basin tend to be more layer parallel than those in the Thetis Basin, which are commonly saucer-shaped (Fig. 2). This morphological-depth relationship is typical of sill complexes (Planke et al., 2015).

Sills are not imaged beneath the extrusive facies (e.g. Inner Flows; see Planke et al., 2000) and are absent within the Danmarkshavn Ridge. Sparse data coverage prevents us from determining the northward extent of the complex in the Thetis Basin. The frequency of the seismic data at the depths at which the sills are found is 10 Hz, therefore the sills need to be >200 m thick to be resolved and >50 m thick to be detected. Although imaging of deep sills and distinguishing sills from multiples beneath the first high amplitude sill reflection event is challenging, intersecting seismic surveys indicate that the sills are vertically stacked, with each complex containing ≥4 sills which decrease in number toward the basin margins.

Linked to the tips of the sills by vertical chimney zones of disturbed reflections are a series of hydrothermal vent complexes. These vents have eye-, dome- and crater-type upper parts, similar to those on the conjugate Norwegian margin (Planke et al., 2005). The eye- and dome-type vents have sub-parallel, prograding internal reflections whilst the crater-type vents have internal reflections which vary from chaotic to parallel. We calculate the upper part of the vent complexes are 36–504 m in height. The diameter of the vents ranges from 0.7–11 km (e.g. Fig. 4). Within the Thetis Basin, the upper parts of all vents are located at a consistent stratigraphic horizon which is onlapped by overlying reflections; this is identified as the Vent Horizon (VH). Onlap relationships indicate the VH represents the paleosurface at the time of sill intrusion. Within