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3D STRUCTURE AND FORMATION OF HYDROTHERMAL VENT COMPLEXES AT
THE PALEOCENE-EOCENE TRANSITION, THE MØRE BASIN, MID-NORWEIGIAN
MARGIN

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ABSTRACT

The mid-Norwegian Margin is regarded as a type-example of a volcanic rifted margin, formed prior to, and during, Paleogene break-up of the NE Atlantic. The area is characterized by the presence of voluminous basaltic complexes such as extrusive lava and lava delta sequences, intrusive sills and dikes, and hydrothermal vent complexes. We present a detailed 3D seismic analysis of fluid and gas induced hydrothermal vent complexes in a 310 km² area in the Møre Basin, offshore Norway. We find that formation of hydrothermal vent complexes is accommodated by deformation of the host rock when sills are emplaced. Fluids are generated by metamorphic reactions and pore fluid expansion around sills and are focused around sill tips due to buoyancy. Hydrothermal vent complexes are associated with doming of the overlying strata, leading to the formation of draping mounds above the vent contemporary surface. Both the morphological characteristics of the upper part and the underlying feeder structure (conduit zone) are imaged and studied in 3D seismic data. Well data show that the complexes formed during the early Eocene, linking their formation to the time of the Paleocene-Eocene thermal maximum (PETM) at c. 56 Ma. The well data further suggest that the hydrothermal vent complexes were active for a considerable time period, corresponding to a c. 100 m thick transition zone unit with both primary *A. Augustum* and re-deposited very mature Cretaceous and Jurassic palynomorphs. The newly derived understanding of age, structure, and formation of hydrothermal vent complexes in the Møre Basin contributes to the general understanding of the igneous plumbing system in volcanic basins and their implications for the paleoclimate and petroleum systems.
INTRODUCTION

At the mid-Norwegian Margin, the Paleocene-Eocene interval represents the time period of the early NE Atlantic rifting and continental break-up (Gibb and Kanaris-Sotiriou, 1988; Bell and Butcher, 2002). Evidence for volcanic activity in sedimentary basins is found along the entire European NE Atlantic margin (e.g. Doré et al., 1999). Volcanic processes and deposits may have significant impact on the structural and geodynamic development of the rifted margin and associated sedimentary basins, i.e. the Karoo Basin, the Rockall Basin, the Faroe-Shetland Basin, and the Neuquén Basin (Svensen et al., 2012; Magee et al., 2014; Smallwood and Maresh, 2002; Schofield et al., 2017). The Møre Basin study area is located beneath the outer shelf and slope region offshore mid Norway, and shows classical examples of how volcanic activity and igneous intrusions within sedimentary strata may impact the basin structure (Skogseid et al., 1992; Brekke, 2000). Short and long term impacts includes deformation, differential compaction, uplift, heating of host rock and pore fluids, metamorphism, and the formation of hydrothermal vent complexes.

The distribution and nature of volcanic intrusions and associated hydrothermal vent complexes represent key elements in basin evolution, and it is therefore important to better constrain the age of the main volcanic episode and the coherent venting processes. In addition, the venting process has been related to greenhouse gas expulsion to the atmosphere, thereby providing a link to the transient climatic shift during the Paleocene-Eocene Thermal Maximum (e.g., Svensen et al., 2004). The climatic records during this period are well documented from a number of sections worldwide (Zachos et al., 2001; Zachos et al., 2008), and recent results show that the only drilled HVC in the Vøring Basin (borehole 6607/12-1) formed during the PETM plateau, thereby demonstrating a relationship between the long duration of the PETM and the gas.
venting (Frieling et al., 2016). Similar Kilometer-scale hydrothermal vent structures have been
described elsewhere in seismic data (e.g., Planke et al., 2005; Hansen et al., 2005; Grove 2013)
and in outcrops (e.g., Svensen et al., 2006) in several basins. These vent structures all share
structural similarities, including complete brecciation, fluidization and inward dipping reflections.
However, the upper parts of these vents imaged on seismic data often exhibit distinct structural
features (eye, crater and dome shapes). The mechanisms leading to different structures are
currently unknown. In addition, the structural features observed on seismic data differ from those
described in field and outcrop studies. It is not clear whether the differences between seismic
features and geological observations are real structural differences or the result of artifacts in the
seismic images.

The aim of this study is to increase our understanding of the formation and age of
hydrothermal venting in volcanic basins. This study is based on structural imaging and detailed
mapping of morphological features in a 3D seismic survey acquired in the Møre Basin, together
with well-log data and analyses. We further apply a new workflow to better constrain the
complex structures of hydrothermal vent complexes on seismic images, using a combination of
qualitative laboratory models and advanced seismic modeling. These results may help to identify
potential artifacts related to fluid and sediment remobilization in seismic images.

GEOLOGICAL SETTING MØRE BASIN

The mid-Norwegian margin developed through a series of post-Caledonian rift phases
that culminated with the onset of seafloor spreading at ca. 56 Ma in the Norwegian-Greenland
Sea (Mosar et al., 2002). The Møre and Voring margin segments, each between 400-500 km long,
are separated by the Jan Mayen Fracture Zone (Figure 1; Faleide et al., 2008). The deep Møre
and Vøring basins formed during Late Jurassic–Early Cretaceous rifting episodes (Figure 1). The basins are characterized by thick Cretaceous sedimentary accumulations, and can in places reach up to 13 km, of which 8-9 km comprises the Cretaceous succession (Gernigon et al., 2003). Continental breakup was accompanied by large-scale igneous activity, forming kilometer-thick basaltic complexes on both sides of the continent-ocean boundary (Brekke, 2000). At the same time, extensive igneous sheet-intrusions were emplaced in the Møre Basin, and hundreds of hydrothermal vent complexes were formed by pressure increase and devolatilization in the contact aureoles around the sills (Planke et al., 2005; 2015; Svensen et al., 2004, 2010; Frieling et al., 2015). The Møre Basin subsequently subsided, leading to deposits of marine mud and ooze, and finally thick sequences of glacially-derived sediments and slide material (Faleide et al., 2008).

### Stratigraphy

The seismic well-tie in the Paleogene and Neogene (Cenozoic) successions are confident (Figure 2). However, the sequences below 4.4 s TWT of late Cretaceous age are difficult to tie because of imaging problems and lack of well data. The stratigraphy includes five formations and is described from the oldest to youngest unit. In the study area, the lowermost interpreted formation is the Springar Formation. It consists of predominantly greyish-green claystones interbedded with stringers of carbonates and sandstone (Dalland et al., 1988). Limestone beds exceeding over ten meters in thickness interbedded with shale are encountered at an interval from 4076 – 4140 meters (MD). The Springar Formation is overlain by the Paleogene Tang Formation which is characterized by dark grey to brown claystone with minor sandstone and limestone (Dalland et al., 1988). The lithology of the lowermost part and transitional zone into
the Springar Formation is interpreted as the Danian sandstone reservoir of the Tulipan discovery.

These sandstone layers are typically 1-7 meters thick and interbedded with siltstone and claystone in the depth range between 3901-4000 m (MD).

The Tare Formation is defined by dark grey, green or brown claystones with some thin sandstone stringers and a variable content of tuffaceous material. The tuff content is highest towards the basal section of the formation, with increasing volume in the lowermost Eocene sediments. The Tare Formation is overlain by the late Eocene to middle Miocene Brygge Formation, which is part of the Hordaland Group (Deagan and Scull, 1977; Dalland et al., 1988).

The Brygge Formation consists mainly of claystone, interbeds of sandstone and bio-siliceous ooze (Hjelstuen et al., 1997). The two uppermost formations in the study area are the Lower Miocene to recent Nordland Group which is sub divided into the Kai Formation and the upper Pliocene Naust Formation (Dalland et al., 1988). The Kai Formation consists of alternating claystone, siltstone and sandstone with interbedded limestone, and the Naust Formation mainly comprises claystone and siltstone.

Formation and source of hydrothermal vent complexes (HTVC)

The formation of HTVC’s requires that fluid pressure within contact aureoles overcomes the rock strength and the lithostatic pressure. Instantaneous overpressure-release occurs if the pressure build-up is faster than the pressure release and seepage in the host-rock. Jamtveit et al. (2004) and Nermoen et al. (2010) proposed a model where the venting mechanism is based on boiling and expansion of pore water as the cause for pressure build-up. If the fluids generated are greater than allowable through Darcy flow, a critical state is reached and venting can occur (Jamtveit et al., 2004; Nermoen et al., 2010). Lithological information from the Møre Basin
show that the host rock consists of primarily mudstone, claystone and sandstone at the HTVC
interval. Mudstone heating can result in clay mineral dehydration and organic matter breakdown
to CO$_2$ and CH$_4$, contributing to overpressure generation (cf. Svensen et al., 2004, 2007; Aarnes
et al., 2010). The fluid generation is critically dependent on the heat transfer from the sill and is a
function of host rock properties, sill thickness and temperature, and the geothermal gradient
(Aarnes et al., 2010; Grapes, 2010).

Fluids generated in contact aureoles have low densities and a greater buoyancy compared
to the pore fluids in the sedimentary rocks. The presence of lighter components, such as methane,
may dissolve in the fluids or migrate as a gas phase during the formation of HTVCs (Svensen
and Jamtveit, 2010; Wang and Manga, 2015). The volume of these carbon-bearing gases depends
on the total amount of organic carbon in the host rock (Whitaker, 1986).

DATA AND METHODS

Seismic and well data

The seismic data used in this paper consists of a subsection (310 km$^2$) of the ST0105
(Tulipan) 3D survey (2100 km), collected and processed in connection with the PL251 license in
2005. The survey is situated in the western part of the Møre Basin, offshore mid-Norway (Figure
1). The data are 3D time migrated, and the overall quality is regarded as very good. The main
frequency spectrum of the data is about 20-40 Hz (3.7-4.5s TWT). This implies a dominant
wavelength of 30-50 m, corresponding to a vertical seismic resolution of about ~10 m ($\delta h=\lambda/4$:
one quarter of the dominant wavelet). The data are regarded as zero-phase, and displayed so that
white/blue (depending on color scheme) denotes increase in acoustic impedance.
Borehole check-shot and conventional wireline log data from the Tulipan well (6302/6-1; Figure 2) show that velocities vary from about 2000 m/s at the seafloor to more than 3000 m/s at the base of the interpretation interval. Finally, 6302/6-1 borehole stratigraphy, petrography, and biostratigraphy reports were made available from Statoil. Results from these reports are summarized in Figure 2.

Seismic interpretation

In total, 14 seismic horizons were interpreted regionally in the study area based on the seismic well-tie to 6302/6-1 (Figure 2). The interpretation focused on the Paleocene and Eocene sequences, in particular the Intra Brygge 2, Top Tare, Intra Tare, HV1 and HV3 horizons. These horizons are well-defined, continuous events in the study area (Figure 2) and were used to define the upper part of the hydrothermal vent complexes. In addition, sills and lava flows where interpreted using the approach of Planke et al. (2015).

The upper part of each vent complex is defined as a domed region with down lapping internal reflections on HV1. In 3D, the dome structures display an ellipsoidal geometry. Thus the lengths of both minor and major axes could be determined. The conduit height is defined as the depth between the termination of the interpreted underlying feeder sill and the HV1 surface. The depth to the sill is not always clearly defined because a vent complex may have originated from deeper, poorly imaged sills.

Sandbox and seismic modeling

One of the main challenges regarding interpretation of seismic images and complex geological structures is to avoid potential pitfalls and miss interpretations due to e.g., seismic
artifacts, illumination and resolution issues. To overcome this challenge, new seismic modeling appears as a valuable tool to separate the real structure from a seismic artifact (Lecomte et al., 2015).

The principle of seismic modelling is to use geometric and attribute input parameters to produce a synthetic seismic image. The comparison between the input geometry and the resulting image is a key aspect of deciphering between the real structures and the artifacts on seismic data.

As geometric input parameter for hydrothermal vent complexes, a laboratory experiment of fluid overpressure structures in granular and unconsolidated media has been undertaken. These experiments proved very useful to unravel the dynamics of venting, with applications to pockmarks, mud volcanoes, hydrothermal vent complexes and kimberlite pipes (Nermoen et al., 2010; Haug et al., 2013; Galland et al., 2014). Importantly, the structures simulated in the laboratory are comparable in geometry to the structures observed in the field, although the laboratory models have to be upscaled.

The sandbox experiment setup consisted of a vertically orientated, air-filled Hele-Shaw cell measuring 60x60 cm (Haug et al., 2013; Nermoen et al., 2010). The cell is sealed at the bottom and the vertical sides, while the top part of the cell remains open. Each experiment was prepared by slowly pouring alternating olivine sand and quartz sand through a funnel, from the top of the cell to a desired filling height. Over-pressurized air from a constant supply was injected into the sand through an inlet placed within the bed. The flow velocities in the experiment were regarded as constant, since the air supply was induced at a uniform pressure throughout the experiments. Digital images during the experiment were captured at 7 frames per second using a high resolution camera.
The most representative picture obtained during the sandbox experiment served as a target model for the synthetic seismic modeling. The target model was implemented into the modelling software (SeisRox) as a 2D layer model. The sand makes up the basic geometry of the model, and is defined by the different layers related to the sedimentary sequences and the coherent change in elastic values (Vp- and Vs- velocities). The following assumptions were further implemented:

- The horizontal and vertical sizes of the background picture are defined as 1800 m and 850 m, respectively, based on dimension analysis done during seismic interpretation.

- Velocity data available from sonic logs at the HTVC ranges from Vp ~ 2000-2500 m/s and Vs ~ 1100-1800 m/s, increasing with depth.

- Two sets of velocities properties (Vp and Vs) were implemented to create the impedance/reflectivity model. These values range between: Vp ~ 2000-2300 m/s and Vs ~ 1200-1300 m/s.

- Density in the model varies from 2.0-2.2 g/cm³.

- The seismic properties within each zone are homogeneous and identical throughout the sequence, with no internal reflections.

- Seismic modeling 20 Hz, corresponding to the HTVC interval.
RESULTS

Distribution of sills and vent complexes

All HTVC’s mapped in this study are related to underlying sills. The majority of the vent complexes are associated with the saucer shaped Tulipan sill located in the central part of the study area (Schmiedel et al., in press). Due to the distinctive sill geometry, it is regarded as an important element in explaining the behavior, position and structural development of the HTVC’s. The extensive sill complex in the Tulipan 3D cube is interpreted based upon the same method as the horizon interpretation (e.g. Planke et al., 2015). The sills are identified as high amplitude reflections within the sedimentary strata, and display local transgressive segments.

Three sills have been mapped and picked as separate horizons. The lowermost sill is difficult to map with confidence, due to the acoustic masking of the overlying intrusions. The Tulipan sill is a saucer-shaped intrusion, and is easily recognized in the seismic section. Figure 2 shows that the Tulipan sill is forcing a dome-shaped morphology of the overlying Base Carbonate, Top Springar and Top Danian horizons (Schmiedel et al., this volume, in press). The Base Carbonate and Top Springar horizons are intersected and pierced by the transgressive segments of the sill, resulting in the most prominent HTVC’s in the study area.

Figure 4 shows the relationship between the underlying sills and the position of the different HTVC’s. HV1 is the horizon of which the dome reflections are down-lapping. The spectral decomposition horizon in Figure 4 shows a clear relationship between the geometry of the underlying sills and the location of the vent complexes. Most of the vent complexes are seen along the outer margins of the Tulipan sill. The differences in rim elevation at the sill margin cause the conduit zones to shallow and deepen, depending on the sill position and elevation.

Deeper situated vents are observed where the sills are less inclined.
Seismic characteristics of the HTVC

The recognition of the hydrothermal vent complexes is based primarily on interpretation of two horizons in the Paleogene sequence, HV1 and Top Tare (Figures 2 and 4). The reference horizon HV1 is defined by the seismic characteristics and well-defined geometry of the upper part of the vent complexes. In this study, 13 individual vent complexes have been identified and analyzed (Figures 4 and 5).

The upper part of the HTVC is seen in the seismic cross-section as a dome down lapping onto the HV1 paleosurface (Figures 5 and 6). The geometry and structural context display similarities to vent complexes described elsewhere on the Norwegian Margin and in the Faroe Shetland Basin (Planke et al., 2005; Schofield et al., 2015). However, only vent complexes with dome-shaped upper parts are present in the study area. Slight depressions are observed at the base of some structures, but the overall structure consists of a down lapping dome, and no eye- or crater-shaped features are found as in the study of Planke et al. (2005). All of the vent complexes mapped in this study display a dome feature above HV1. Not all the domes are down lapping onto HV1, but the majority do (11 of 13), suggesting that this is a dominant behavior of the HTVC’s in this part of the Møre Basin. Figure 6 illustrates domes on the HV1 horizon where the height of the structure is about 0.1 s (TWT), corresponding to 80-100 m. The domes are used to give a qualitative measurement of the geometries of the upper part of the vent complexes (Table 1; Figure 7).

The HTVC depth is essentially a measurement of the dome structural relief, made by defining a datum linked to the underlying HV1 horizon (Figure 3). Table 1 present the sizes of the 13 individual HTVC’s, showing sizes in the 70-120 m range. The horizons above HV1 are
characterized by a series of convex structures, which are described as draped mounded structures. The term ‘mounded structure’ is used as a descriptive term in this paper to define the topographic relief of the dome above HV1 (Figure 5). To determinate the extent of these structures the horizons was picked as a well-defined, high amplitude and continuous stratigraphic boundary, defined by the presence of the uppermost part of the convex mounded reflections.

HTVC's are observed below mounding structures on the Top Tare horizon. They typically display sizes ranging from 600-2000 m in diameter and 70-120 m in height, with an elevated time ratio of 0.1 s (TWT). These mounded structures are exclusively observed in the Paleocene-Eocene transition zone and the lower part of the intra Eocene interval. This interval is defined by a relatively abrupt decline in gamma and sonic response in well 6302/6-1 (Figure 2). In the stratigraphic completion log the interval is described as claystone with thin sandstone stringers with variable content of tuffaceous material. The sonic values in this interval could suggest a transition to more under-compacted and homogeneous clay-sandstone compositions beneath the tuff deposits.

Vent conduit zone

The vent conduit is interpreted as the disrupted, altered or brecciated zone where fluids and mobilized sediments migrated towards the paleosurface. The conduits are seen as disrupted reflections, resulting in a chaotic character of the originally stratified host sedimentary rocks. The 3D data show the conduits as vertical zones in the seismic data, where the amplitudes and reflections are distorted (Figures 3 and 5), consistent with earlier work in the basin and elsewhere (e.g. Heggland, 1998).
The conduit zones show variable morphologies. Some are conical and become thinner downwards towards the sill tip, while others display cylindrical morphologies. Not all the conduit zones display a traceable path from the dome down to their origin. In cases where the flow pattern is diverted by displaced fault blocks or magmatic bodies, the prediction of the sill and aureole origin is difficult. However, the conduits do not appear to follow fault planes in general, and systematic fault cutting is not observed.

In the cases where the conduit zones and the links to sills are uncertain, it might be a result of seismic imaging and detection problems. The overburden might also play a role in the interpretation. High amplitude reflections may mask underlying strata, or create seismic artefacts by obscuring the underlying reflections (Schroot and Schüttenhelm, 2003). Reflections in the surrounding host strata are often seen to dip towards the conduit zone and upper part of the HTVC. This feature is best observed in the seismic section crossing large HTVC’s.

Sandbox modelling results

Each of the experiments started with similar litostatic stress conditions for the granular bedding in the Hele-Shaw cell (Figure 8). Compressed air from a pressurized tank was gradually imposed through the inlet by manually increasing the air flux using a valve. The pressure was increased slowly until the predefined supply pressure was reached and the fluid-induced deformation of the matrix was obtained.

In experiments where the simulated overburdens exceeded 9 cm, a static bubble formed on top of the inlet (Figure 8). The bubble did not change size (width or height) through time, at a given (constant) pressure. The presence of the static bubble also induced lateral compaction of the matrix, together with a moderate uplift resulting in two steeply dipping reverse shear bands.
on each side of the inlet (Figure 8, t3 and t4). The dip angle, and diameter of the conical reverse shear bands are influenced by the filling height, with increasing values for additional material filling. When further increasing the pressure to values beyond the equilibrium threshold, the bubble rapidly moved towards the surface initiating the fluidization.

Fluidization is characterized by rapid upward transport of the grains together with the ascending bubble. This transport enables convective movement aligned with the inlet and at the center of the structure. This convective flow generated inward dipping beds at both sides of the fluidization zone. The concentration of fluidized deformation was centralized within the reverse shear bands. At the surface above the fluidization zone, crater deposits formed as grains were erupted (Figure 9).

We have compared the results from the Hele-Shaw cell with those from the seismic interpretation. Although HTVC’s are symmetrical 3D structures and the sandbox experiment resulted in two dimensional confined structures, correlation between basic parameters such as height, width and length is still valid. Figure 10 shows similarities between at the upper part of the HTVC’s compared to the upper part of the sandbox structures. The plots indicate how crater/dome structures scale approximately linearly with the conduit/filling height ratio. This is a trend also obtained from the seismic data, where taller conduit zones are associated with larger surface structures (Table 1). Although a linear correlation may not represent the best fit in terms of the actual HTVC’s, the height/width dependency is significant. Therefore, the sandbox models capture first-order features of the natural HTVC.

Seismic modelling
By estimating a simple overburden model and taking into account the combination of survey/migration aperture, we can retrieve and highlight the illuminated reflections at a given depth interval and reference point (Lecomte et al., 2015). The illumination of the target is in practice depending on the survey geometry and the wave propagation in the overburden, and will also vary according to the location of the target (lateral and depth). Our seismic modelling allowed for direct control of what would be the maximum dip illuminated at the target, i.e., all reflection dips between horizontal and the maximum dip imaged (Lecomte et al., 2016). Three maximum illuminated dips were therefore tested during the seismic modelling procedure (25°, 45°, and 90°), corresponding to limited, reasonable, and perfect (ideal) survey/migration apertures, respectively (Figure 11).

The synthetic model was able to capture complex features of the piercement structure and produce realistic geometries and deformation fields. Although the differences between 25° and perfect (90° max dip) illumination may be subtle, there are differences due to resolution and geometric effects. From the 25° max dip, features exceeding the 25° incline angle will disappear in the seismogram (black arrows in Figure 11). Additionally, the disrupted conduit zone appears as blurry and transparent in the seismogram compared to the 45° and perfect illumination. This observation supports that a narrow survey aperture prohibits steeper reflections to be illuminated compared to a wide aperture. The 45° corresponds to symmetrical illumination of the modelling. Angles exceeding 45° max dip is not illuminated in the seismogram. Note that the steeper dipping reflections in the conduit zone seem to have a more lateral and continuous extension. When comparing the conduit interior between the 45° and the perfect illumination, the latter it is slightly improved with respect to reflection strength.
The hydrothermal vent complexes provide evidence for focused fluid and gas migration in the Møre Basin close to the Paleocene-Eocene transition. A number of questions arise from our mapping, including aspects of the detailed interpretation of the seismic data and the age of the HTVC’s. The key to these questions can be constrained by examination of the seismic and stratigraphic data, and the experimental and synthetic modelling. The discussion below focuses on the HTVC’s as one complete system, including morphology, formation mechanisms and age correlations.

Dome shape and differential compaction model

A characteristic feature associated with explosive volcanism of hydrothermal venting is the formation of craters (Nermoen et al., 2010; Haug et al., 2013, Galland et al., 2014). The opposite is found regarding the HTVC’s interpreted in the 3D cube, i.e., domes and not craters. The formation of HTVC’s at the HV1 horizon shows a characteristic down-lapping dome structure on the paleosurface defining the upper part (Figure 6). Differential compaction is a mechanism that may explain the doming above the HTVCs.

All materials will compact due to gravitational stresses when loaded. Differential compaction develops for instance in inhomogeneous sedimentary deposits, where the material properties vary (e.g., Miles and Cartwright, 2010; Jackson, 2012; Zhao et al., 2014). Variation in how the different materials behave during this process is dependent on their composition and porosity. The result can be seen as local areas compacting more than others, and that geological structures may be affected geometrically during compaction stresses (Figure 12). This process has previously been described in terms of the upper vent geometry by Skogseid et al. (1992) and
Planke et al. (2005), where it was considered as a possibility for the vent-fill to compact less than the surrounding strata, thus causing the characteristic dome morphology.

The presence of long-lived seepage through vents from underlying strata (e.g. Svensen et al., 2003; Iyer et al., 2013) could also have contributed to reduced compaction of the vent structure. If these fluids migrated and were trapped in the upper vent structure by the deposition of overlying sealing sediments, overpressure could have developed which in turn may have inhibited further compaction.

**HTVC formation and the sandbox experiment**

It is clear that the HTVC’s result from focused fluid flow to generate the structural features seen in the seismic data. We have identified similarities when comparing seismic cross-sections of HTVC’s with the sandbox experiments (Figures 3 and 9). When fluid pressure was increased beyond the equilibrium threshold, fracturing and brecciating developed above the source. The fluidized zone in the sandbox experiment acted as the conduit zone in the natural setting, a pathway for fluids to reach the surface. The fluidization in the sandbox experiment developed two regions where the first consisted of a narrow conduit zone and the second an upper crater zone (Figure 9). These two morphological features can be correlated to the upper and lower part of the HTVC’s (cf., Jamtveit et al., 2004; Planke et al., 2005).

Field data shows that the HTVC’s contain brecciated sedimentary rocks with lithological differences compared to the surrounding strata (Jamtveit et al., 2004; Svensen et al., 2006). Similar findings are evident from the conduit zone in the sandbox experiment. Moreover, both field observations, seismic and experimental data show well-developed inward dipping strata towards the conduit zone (e.g., Planke et al., 2003; Svensen et al., 2006). The experiment time-
lapse photographs of Figure 8 shows convective flow during material transport, resulting in volume reduction followed by collapse and the generation of inward dipping beds.

The main difference between the sandbox models and the seismic data is the shallow structures: the sandbox exhibit well developed crater morphology above the in-filled fluidized conduit zone, whereas HTVC’s interpreted in the 3D cube exhibit domes. As mentioned earlier, we interpret these domes as a result of differential compaction, a process that cannot be modeled in the sandbox.

Synthetic seismic

The synthetic modelling emphasizes the importance of internal structures in generating seismic amplitude anomalies. Figure 11 shows a comparison between the different modelling runs. Even though the resulting seismic images produced are generically similar, there are clear structural differences. One of the most prominent characteristics when comparing the 25° to 45° max dip is how the reflections in the images are displayed (Figure 13). By widening the survey distance and migration aperture in the model, steeper reflection dips at a given reference point are obtained. Perfect illumination has the widest survey/migration aperture, and the 25° the narrowest. Comparing the seismic and the synthetic section, the near horizontal reflections are displayed properly, but this is not the case for the dipping reflections. The combination of survey aperture and layer dip makes for two different structural interpretations of the seismograms. When comparing these results to the actual seismic section of the HTVC’s, we find that the dipping reflections in the conduit zone usually do not exceed c. 45°-50°. From the seismic modelling we found out that 45° max illumination dip was reasonable for the considered
overburden model and a standard migration aperture value. This may imply that the processed
data is unable to properly visualize reflections above this angle. A reasonable maximum
illuminated dip is taken to be about 45°, and seems to fit between our modelling estimation and
what is observed on the actual images.

A direct implication of this is that strongly dipping structural features within the HTVC’s
can be overlooked or misinterpreted (Figure 13). The synthetic modelling thereby provides a
method for more confident interpretations of geological features, plus the ability to validate
seismic attributes and artefacts to avoid pit-falls and misinterpretations.

**Age and evolution of the Møre Basin vent complexes**

Age determination of the HTVC’s in this study is based on the seismic interpretation,
well-tie correlations and published palynological data focusing on the sediments at the upper
HTVC interval. The interval between the HV1 and HV3 horizons represents the development
and emplacement of the HTVC’s. These observations include the intrusive nature of the conduit
zone below this transition zone, down-lapping domes, radial faults and tuffaceous claystone at
the paleosurface of HV1. From the well data and check-shots, the measured depth of this interval
is correlated to be between 3350 and 3450 m (Figures 14 and 15).

The biostratigraphic evidence from this transition zone comprises a somewhat enigmatic
assemblage with mixed age biostratigraphic indicators between the clear signatures from the
underlying Tang and overlying Tare formations. Clear and clean occurrences of the dinocyst
*Aspectodinium augustum* are identified at 3350 and 3390 m (last natural occurrence, LO in the
well) which suggests that the interval most likely comprises the TP5A zone of the Earliest
Eocene (Figure 14). This species is widely used as a marker species for the Paleocene-Eocene
transitional (Ali and Jolley, 1996; Passey and Jolley, 2009; Schmitz et al., 2004; Sluijs et al., 2006). Classification of the interval is complicated by the occurrence of older Paleocene palynomorphs (e.g. Tang markers such as Alisocysta margarita, Palaeoperidinium pyrophorum, Areoligera gippingensis, Spiniferites 'membranispina'; note that these did not occur in the expected order) along with the frequent occurrence of Cretaceous fossils like Sidridinium borealis, 'ancient' bisaccates, and Upper Triassic Ricciisporites tuberculatus. The interval may therefore represent the upper parts of the Tang Formation with abundant caving from zone TP5A, or alternatively in situ TP5A with reworking from Tang and older formations. The mixed nature of the assemblage supports significant reworking within the interval and therefore the clear occurrences of Apectodinium augustum are used to support an Earliest Eocene (54.9-55.8 Ma) age for the transition zone and therefore the HTVC development within the Møre Basin study area (Figure 14).

A wide range in thermal maturity of the retrieved fossils is documented from the transition zone suggesting a source near the sill. For instance, some of the Cretaceous and older re-worked fossils are almost black in the 3410-3440 m. Tuffaceous material was also identified within the interval. Along with the high temperature signatures, older sediments and volcanic detritus indicate that both local and basin-wide eruptions, causing plumes of mixed age sedimentary rocks along with their bio-markers (e.g. Schofield et al., 2015), could have contributed to the mixed assemblages of the transition zone at this time.

**Paleocene-Eocene thermal maximum (PETM)**

The HTVC formation coincides with one of the most extreme transient shifts in climate during the Cenozoic. The Paleocene-Eocene Thermal Maximum (PETM) occurred at ~56 Ma...
and lasted between 100-200 kyr (e.g., Norris and Röhl, 1999; Westerhold et al., 2009). This event is associated with a significant temperature rise of the oceans and the atmosphere, together with changes in ocean chemistry and extinction of benthic foraminiferal species traceable in the biostratigraphical record (e.g., Kennett and Stott, 1991; Röhl et al., 2000; Röhl et al., 2007).

The PETM is coeval with the initial opening of the NE Atlantic Ocean (Storey et al., 2007), which has been linked to magma emplaced in the Møre Basin (e.g., Svensen et al., 2004; Frieling et al., 2016). Although no direct evidence for contact aureoles have been identified during the seismic interpretation, contact metamorphism around sills is well understood and lead to the generation of CH₄, CO₂ and H₂O from heating of organic-bearing sedimentary rocks (e.g., Aarnes et al., 2015). Vent complex statistics from both the Møre and Vøring basins by Planke et al. (2005) indicate that potentially thousands of individual HTVC’s formed within the PETM and may have acted as one of the main sources for carbon (Svensen et al., 2004). Sedimentary basins influenced by LIP’s may thus represent settings characterized by rapid release of carbon-bearing gas.

CONCLUSIONS

Seismic mapping in the Møre Basin offshore mid Norway has documented an extensive hydrothermal vent complex of Paleocene-Eocene age. Thirteen individual vent complexes have been mapped within the 310 km² large study area. All the observed venting structures are located above sill intrusions, and are therefore assumed to have develop as a direct consequence of sill emplacement and contact metamorphism. The complex architecture of the HTVC’s may be explained by mobilization of sedimentary rocks from above the sills, caused by local fluid over-pressure and fluid migration. The HTVC’s were formed primarily during explosive eruption of
gases, liquids and sedimentary rocks, resulting in depressions and craters at the seafloor. The upper parts of the HTVC’s are dominated by domes and mounded features measuring up to 2.5 km in diameter and 120 meters in height. The upper parts of the vent complexes terminate consistently at the Paleocene-Eocene transition above the Tang Formation. This study has used state-of-the-art methods to produce unique 3D images of seismic reflection-data together with simulated modelling to map out the HTVC’s within the Møre Basin. The methods utilized, demonstrate how the final analyses can provide new images of sediment deformation and fluid/gas migration patterns using 3D seismic and modelling procedures. Combining these makes it possible to recognize geometries with considerable confidence, along with mapping important relationships between fluid-flow pathways and structural behavior with high precision.

By implementing well-tie correlations and biostratigraphical analysis, the age of these structures are within the 54.9-55.8 Ma range. This period is characterized by intrusive events during the initial volcanism phase at the mid-Norwegian Margin, corresponding to the NE Atlantic break-up. The hydrothermal vent complexes were likely active for a substantial time period in the earliest Eocene. The vent formation likely corresponds to a c. 100 m thick Tang/Tare transition zone with *A. Agustum* and re-worked Cretaceous and older fossils displaying high maturities possibly caused by contact metamorphism. Timing of the HTVC’s coincides with one of the most extreme climatic shifts in the Cenozoic, the PETM, and our data and conclusions stress the link between the generation and release of carbon gases from the Møre Basin and the global environmental change.

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**Figure 6.** A) 3D seismic interpretation of the v.6 dome structure, down lapping onto the HV1 horizon. B) Corresponding 2D projection of the v.6 dome structure. C) "Variance cube"-slice from the HV1 horizon seen from above. Figure illustrates the 3D mapped and time-slice variance representation of domes v. 4 and v. 6. The variance cube highlights lateral discontinuities such as faults. The fault pattern away from both vents, suggest development simultaneous to the vents formation.

**Figure 7.** Bar diagram showing the dome sizes for the measured HTVC’s in Table 1.

**Figure 8.** Time-lapse sequence of sandbox experiment. (t1): initial configuration of the static bedding. (t2): Static bubble forming at the centered inlet, fluid induced deformation of the matrix. (t3): Gas bubble grows to the surface, triggering the onset of fluidization and eruption of
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Figure 9. Morphological zones defined in the experiment which enables a correlation to the natural occurring HTVC’s.

Figure 10. Comparison-plot between HTVC’s and piercement structures in the sandbox experiment: A) Minor width plotted against the conduit height. B) Major width plotted against the conduit height. C) Crater width plotted against filling height (in sandbox experiment).

Figure 11. Synthetic seismic modelling of a model derived from the sandbox experiment. Elastic properties based on well 6302/6-1 at the HTVC interval. Arrows in uppermost figure highlights how different reflection dips are affected by seismic imaging.

Figure 12. Schematic model displaying key development stages during vent formation. A) Emplacement of intrusion promotes fluid generation and overpressure causing overburden failure and explosive hydrothermal venting which blankets the surrounding area with vent material and older sediments. Large volumes of carbon outgassed into the water column and atmosphere. B) After the initial high energy venting, activity gradually wanes with long-lived gas seepage occurring over many thousands of years and periodically promoting small-scale sediment eruptions, which fill the crater and build up a shallow angle dome. C) Post venting sedimentation blankets the dome and builds up a potentially sealing cover over thousands to millions of years.
Compaction of surrounding strata may exceed that of the hardened or potentially over-pressured vent material resulting in differential compaction and the accentuation of the dome feature.

**Figure 13.** A) HTVC (v.6) seismic section, illustrating how the dipping reflections are displayed in the image, and the uncertainty that follows with steeper dipping reflections. B) 25° max dip illumination in the seismogram. Restricted illuminated reflections above 25°, black arrows indicate structural differences between the two angle dependent models. C) 45° max dip illumination in the seismogram. The dominant frequency of the seismic is 20 Hz.

**Figure 14.** Summary of biostratigraphic age constraints of venting interval. A) Table showing the key taxa distributions correlated with relative age and horizons interpreted at the HTVC interval. Palyno-zones correspond to taxa distribution at given time stages. B) Seismic section and taxa resolution of the HTVC interval. Depth of seismic horizons calibrated with check-shot data from well 6302/6-1.

**Figure 15.** Figure summarizing different data implemented to resolve the key questions regarding the HTVC’s in the Møre Basin. The investigation focus on (1) the vent complex geometries, (2) the induced surface deformation patterns, (3) the intrusions (heat source) relation, as well as (4) the emplacement depth and age of the hydrothermal vent complexes.

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Figure 1

45x26mm (300 x 300 DPI)
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Figure 3
45x24mm (300 x 300 DPI)
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Figure 4
130x201mm (300 x 300 DPI)
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Figure 6
91x98mm (300 x 300 DPI)
Figure 7. Bar diagram showing the dome sizes for the measured HTVC's in Table 1.

Figure 7

240x353mm (300 x 300 DPI)
Figure 8. Time-lapse sequence of sandbox experiment. (t1): initial configuration of the static bedding. (t2): Static bubble forming at the centered inlet, fluid induced deformation of the matrix. (t3): Gas bubble grows to the surface, triggering the onset of fluidization and eruption of material at the structure rim and crater. (t4): Re-sedimentation of piercement structure.

Figure 8

63x47mm (300 x 300 DPI)
Figure 9. Morphological zones defined in the experiment which enables a correlation to the natural occurring HTVC's.

Figure 9
81x45mm (300 x 300 DPI)
Figure 10. Comparison-plot between HTVC’s and piercement structures in the sandbox experiment: A) Minor width plotted against the conduit height. B) Major width plotted against the conduit height. C) Crater width plotted against filling height (in sandbox experiment).

Figure 10
190x395mm (300 x 300 DPI)
Figure 11. Synthetic seismic modelling of a model derived from the sandbox experiment. Elastic properties based on well 6302/6-1 at the HTVC interval. Arrows in uppermost figure highlights how different reflector dips are affected by seismic imaging.

Figure 11
143x244mm (300 x 300 DPI)
Figure 12. Schematic model displaying key development stages during vent formation. A) Emplacement of intrusion promotes fluid generation and overpressure causing overburden failure and explosive hydrothermal venting which blankets the surrounding area with vent material and older sediments. Large volumes of carbon outgassed into the water column and atmosphere. B) After the initial high energy venting, activity gradually wanes with long-lived gas seepage occurring over many thousands of years and periodically promoting small-scale sediment eruptions, which fill the crater and build up a shallow angle dome. C) Post-venting sedimentation blankets the dome and builds up a potentially sealing cover over thousands to millions of years. Compaction of surrounding strata may exceed that of the hardened or potentially over-pressured vent material resulting in differential compaction and the accentuation of the dome feature.
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Figure 13
75x52mm (300 x 300 DPI)
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Figure 15
86x41mm (300 x 300 DPI)
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<th>Dome height (m)</th>
<th>Conduit height (m)</th>
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<td>100 ± 20</td>
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<td>1400 ± 100</td>
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Mechanisms of overburden deformation associated with the emplacement of the Tulipan sill, mid-Norwegian margin.

Interpretation 5:3, SK23-SK38. [Abstract] [Full Text] [PDF] [PDF w/Links] [Supplemental Material]