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The morphology of intrusion-related vent structures and their implications for constraining the timing of intrusive events along the NE Atlantic margin

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Abstract: Intrusion-related vent structures found within Palaeocene sediments and near the Palaeocene–Eocene transition in basins along the NE Atlantic margin have been studied in detail using 3D seismic data. The vents formed at the palaeo-seabed as a result of sill intrusion and the vent fill ranges in composition from entirely remobilized sedimentary to dominantly magmatic. The vents are commonly developed above sill edges and crests in sills to which they are linked by pipe- and diatreme-like structures. The vents also develop above the upper tips of deep-seated faults and at fault intersections. The vents can be used to constrain the approximate timing of igneous sill intrusion and duration of hydrothermal activity. It is estimated that using the seismically constrained stratigraphic context of these vents to establish the timing of sill emplacement is associated with an uncertainty of >100 ka and up to as much as 800 ka. Interpretation of the vents indicates that sill intrusion took place during a number of discrete phases within the Palaeocene and earliest Eocene. These structures and their timing of formation have important implications for climate change studies, basin-scale processes including fluid flow and diagenesis, as well as hydrocarbon exploration.

Mounded vent structures with dome- and eye-shaped cross-sectional geometries are widespread within Palaeocene sediments and near the Palaeocene–Eocene boundary in sedimentary basins along the NE Atlantic margin (Fig. 1). The vents were first described from 2D seismic data from the Rockall Trough (Joppen & White 1990) and Vøring Basin (Skogseid *et al*. 1992), and have more recently been described from 3D reflection-seismic studies in the Faeroe–Shetland Basin (Hodges *et al*. 1999; Bell & Butcher 2002; Davies *et al*. 2002; Trude *et al*. 2003) and the Norwegian margin (Svensen *et al*. 2003, 2004; Jamtveit *et al*. 2004; Planke *et al*. 2005). They occur above igneous sill complexes that intruded into Upper Cretaceous and Palaeocene mud-dominated sediments around the time of continental break-up and onset of sea-floor spreading between NW Europe and Greenland during the latest Palaeocene to earliest Eocene (e.g. Andersen 1988; White 1988; White & McKenzie 1989; Ritchie & Hitchen 1996; Naylor *et al*. 1999; Ritchie *et al*. 1999).

Previous studies, corroborated by the results of this study, suggest that the vents were extruded onto the palaeo-seabed in response to sill intrusion. They have previously been interpreted as (1) dyke-fed volcanic vents and volcanoes (Joppen & White 1990; Skogseid *et al*. 1992; Hodges *et al*. 1999; Davies *et al*. 2002) and (2) hydrothermal vents (Bell & Butcher 2002; Jamtveit *et al*. 2004; Planke *et al*. 2005). Field-based studies of outcrop analogues in the Karoo, South Africa (Gevers 1928; Jamtveit *et al*. 2004) indicate that the composition of these structures ranges from being almost purely volcanic to consisting almost entirely of brecciated sedimentary material altered by hydrothermal fluids.

Importantly, seismic interpretation of overburden relationships and the overall stratigraphic context of the vents can be used to constrain the approximate timing and duration of intrusion independently of radiometric dating of the sills (Davies *et al*. 2002; Svensen *et al*. 2004). This has a number of important implications. It has, for example, been suggested that sill emplacement related to continental break-up in the NE Atlantic played a major role in initial Eocene global warming and that volcanic processes have significant implications for climate change in general (Svensen *et al*. 2004). The vent structures and their plumbing systems described herein are also of considerable interest in relation to a number of basin-scale processes including fluid flow and diagenesis as well as hydrocarbon exploration.

This paper describes the variations in 3D internal and external morphology and structural and stratigraphic context of vent structures mapped in four case-study areas along the NE Atlantic margin, and discusses their composition and relationship with underlying sill complexes. The main discussion in this paper focuses on the use and limitations of the vent structures as indicators of sill emplacement events and the uncertainties associated with this technique for constraining the timing and duration of sill emplacement. Importantly, multiple phases of sill intrusion are documented within both the Faeroe–Shetland Basin and the North Rockall Basin. This has critical implications when trying to establish a possible link between sill emplacement and climate change.

Geological setting

This paper is based on interpretation of 3D seismic surveys located within the North Atlantic Igneous Province. This province formed in response to continental break-up in the NE Atlantic around the Palaeocene–Eocene transition (White 1988; Coffin & Eldholm 1992; Smallwood & White 2002). During that time, complex intrusive networks of sills and near-vertical dykes intruded into Upper Cretaceous and Palaeocene clay-dominated basin fills and lava flows extruded across vast areas (Naylor *et al*.

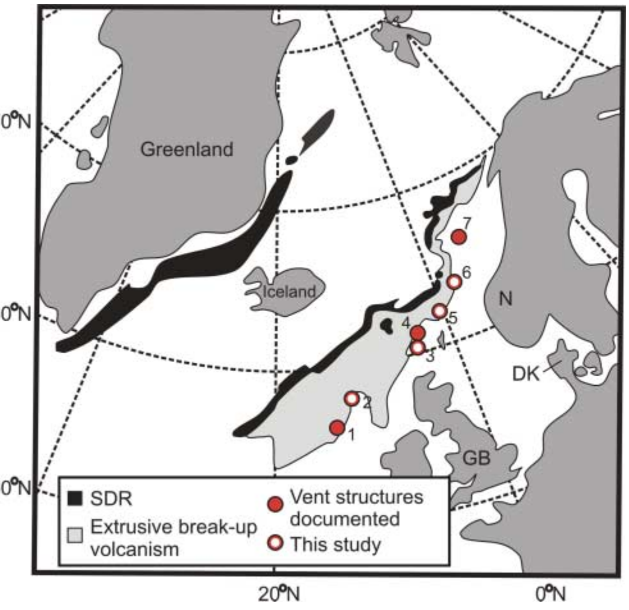

Fig. 1. Map of the NE Atlantic margin (modified from Berndt 2000) showing areas where vents associated with sill emplacement have been documented during this and previous studies. 1, Rockall Trough: Joppen & White (1990). 2, NE Rockall Basin: this study (Tranche 38). 3, Central Faeroe–Shetland Basin: this study (Tranche 4). 4, Faeroe–Shetland Basin: Davies *et al*. (2002) and Trude *et al*. (2003) (both Tranches 61 and 62). 5, Northern Faeroe–Shetland Basin: this study, Hodges *et al*. (1999) and Bell & Butcher (2002) (all Tranche 67). 6, Møre Basin: this study (Solsikke survey area), Svensen *et al*. (2004) and Planke *et al*. (2005). 7, Vøring Basin: Skogseid *et al*. (1992), Svensen *et al*. (2004) and Planke *et al*. (2005). SDR, seaward-dipping reflectors.

1999; Ritchie *et al*. 1999; Planke *et al*. 2000; Berndt *et al*. 2001).

The onset of volcanism throughout the North Atlantic region was at *c*. 62–61 Ma (Smallwood & White 2002) and volcanism continued sporadically until the Early Eocene, with most of the emplacement probably taking place within a time period of only 2–3 million years around the time of continental break-up at 56–53 Ma (White 1988; Smallwood & Maresh 2002; Smallwood & White 2002). The detailed timing of sill intrusion is, however, poorly constrained, as dating has relied almost exclusively on radiometric methods that are often erroneous because of alteration and poor sampling of sills penetrated by boreholes (Gibb & Kanaris-Sotiriou 1988).

Data and methods

Four 3D seismic datasets from basins along the NE Atlantic margin provided by the hydrocarbon industry have been used in this study (Fig. 1 and Table 1). The datasets cover a total area of *c*. 4000 km^2 within the northeastern Møre Basin, the northern and central Faeroe–Shetland Basin, and the NE Rockall Basin. Some biostratigraphic data have been made available for this study and mapped seismic horizons have been dated where possible. An average host-rock seismic velocity of 3000 m s^{-1} (see Bell & Butcher 2002) has been applied. The vertical axis on seismic sections is two-way travel time (TWT). All seismic sections are displayed with black indicating peak amplitudes.

Mapping of igneous sills

The vent structures described herein are found above igneous sill complexes that are well imaged by seismic data (Fig. 2) as a result of a high contrast in acoustic impedance (velocity and density) between the igneous material and the sedimentary host-rock (Badley 1985). Igneous sills appear as high-amplitude continuous reflections that are often abruptly terminated and easily distinguished from surrounding stratal reflections (Fig. 2a). Many of the sills transgress stratigraphy discordantly and adopt concave-upward cross-sectional geometries that when mapped in 3D exhibit saucer-shaped geometries (Fig. 2b and c; Hansen *et al*. 2004). Individual sills may be linked through sill–sill junctions and form highly interconnected sill complexes that cover large areas and may extend for >10 km vertically (Hansen *et al*. 2004).

Mapping of vent structures

Intrusion-related vent complexes were informally defined by Planke *et al*. (2005) as ‘pipe-like complexes formed by fracturing, transport and eruption of hydrothermal fluids and sediments’. In vertical seismic sections the vent structures are commonly recognized as localized dome- or eye-shaped bodies of accreted rock that are delimited in seismic data by mapping the seismic reflections that form their lower and upper boundaries (e.g. Fig. 3). It has not been possible to correlate the vent horizons between the case-study areas because of limitations in the 2D seismic data coverage available to this study.

Detailed 3D seismic interpretation of vent structures

The vent structures show variations in morphology and structural and stratigraphic context, and this is exemplified in the following descriptions of a selection of representative vents. The 3D seismic examples demonstrate differences in host-rock relationships, overall vent geometry, internal morphology, and relationships with the underlying sill complexes. Further, the interpretation documents the occurrence of these structures along the length of the NE Atlantic margin, including the NE Rockall Basin where they have not previously been documented. The general findings within each of the four case-study areas and previous seismic-based studies of similar structures are summarized in Table 2.

Northern Faeroe–Shetland Basin

Vents are developed at two stratigraphic levels within Tranche 67 (T67) of UK Quadrant 219 located in the northern Faeroe–

Table 1. *Summary of the properties of 3D seismic case-study surveys*

Survey	Area (km^2)	Line spacing (m)	Phase	Polarity	Dominant frequency (Hz)	λ /2 (m)
Tranche 67	600	25	Zero	Reverse	*c*. 35	*c*. 80
Tranche 4	730	25	Minimum	Normal	*c*. 25	*c*. 110
Solsikke	1050	25	Zero	Reverse	*c*. 38	*c*. 75
Tranche 38	1400	25	Zero	Normal	*c*. 35	*c*. 80

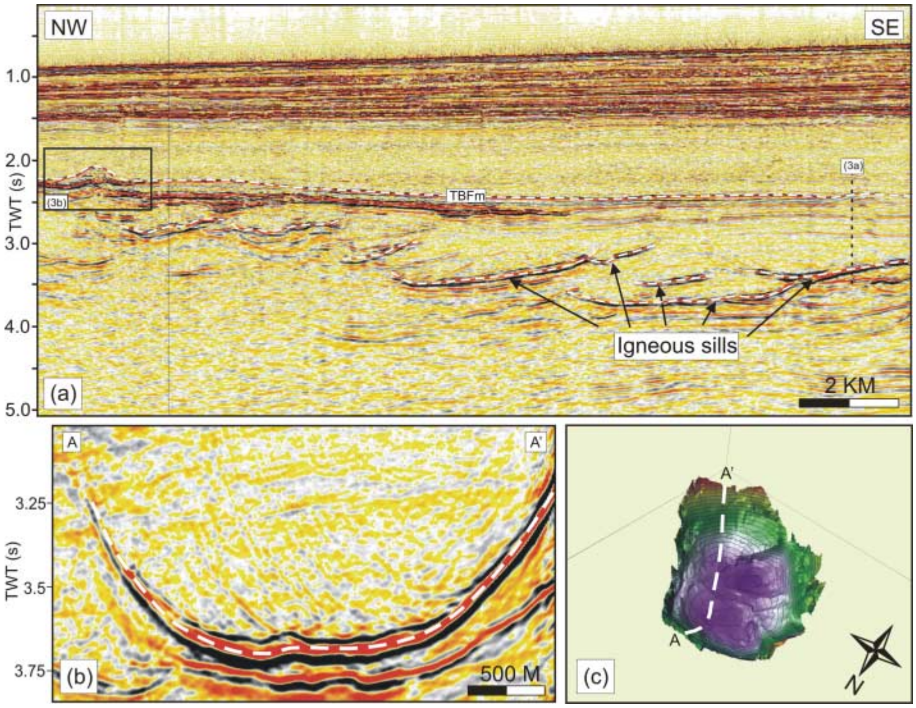

Fig. 2. The seismic expression of igneous sills. (**a**) Seismic cross-section showing a number of igneous sills that were intruded into mud-dominated sediments in the northern Faeroe–Shetland Basin (T67) during the Palaeocene and earliest Eocene. They appear as high-amplitude, continuous reflections that are easily distinguished from the surrounding stratal reflections. (Note location of Fig. 3a and b.) TBFm, Top Balder Fm. (**b**) Close-up of an igneous sill with a characteristic concave-upward cross-sectional geometry. (**c**) A 3D display showing the saucer-shaped geometry of the sill shown in (**b**). The sill has a slightly elongated saucer-shaped geometry and measures 4 km by 6 km, covering an area of 21 km^2. The sill has a vertical relief >500m. Contour interval is 50 ms.

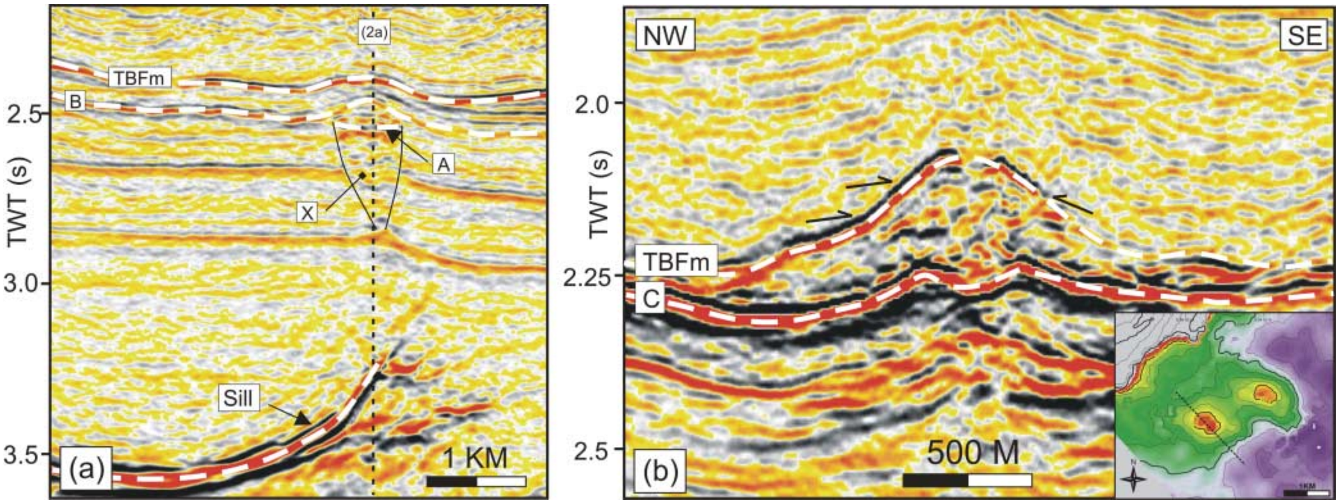

Fig. 3. Seismic cross-sections illustrating the character of vent structures in the T67 survey area located in the northern Faeroe–Shetland Basin. In this area vent structures are found at two discrete stratigraphic levels overlying an interconnected network of sills previously described by Hansen *et al.* (2004). TBFm, Top Balder Fm. (**a**) Close-up of vent structure imaged within Palaeocene stratigraphy immediately above the tip of an underlying sill. The vent is bound downwards by horizon A and upwards by horizon B. A downward-tapering cone of disrupted seismic reflections (X) is seen immediately underlying the vent. (**b**) Close-up of a vent structure developed near the Palaeocene–Eocene boundary. It should be noted that the upper vent boundary (TBFm) is onlapped by overlying stratal reflections. The vent is downwards defined by horizon C. Inset is a contoured time–structure map of the TBFm horizon. Contour interval is 25 ms.

Shetland Basin (Fig. 3). Correlation with exploration well 219/27-1 indicates that the deeper vent level is Late Palaeocene in age, whereas the shallower vent level developed near the Palaeocene–Eocene transition. The majority (>80%) of the vents developed at the stratigraphically deeper level and a representative vent is illustrated in Figure 3a. It is delimited downwards by a locally mapped, flat-lying, moderate- to high-amplitude positive reflection (A) and upwards by a continuous moderate-amplitude positive reflection (B). The vent exhibits an overall dome-shaped geometry with a diameter of 1 km and vertical relief of 120 m. The upper vent boundary exhibits a divergent relationship with the overlying strata. The vent is located *c*. 750 m above the cross-cutting tip of an underlying sill, and a poorly defined downward-tapering cone of low-amplitude discontinuous reflections (labelled X in Fig. 3a) is seen immediately underlying the vent.

A vertical section through a vent developed at the stratigraphically shallower level is shown in Figure 3b. It is delimited

Table 2. *Summary of the geometric characteristics, stratigraphic context and proposed origins of previously described vent structures, as well as those interpreted in the case-study areas*

	Data type	Location	Shape	Diameter (km)	Height (m)	Flank dips (compacted)	Age	Fill	Origin
Joppen & White (1990)	2D seismic	Rockall Trough					Late Palaeocene		Dyke fed
Skogseid *et al.* (1992)	2D seismic	Vøring Basin	Elliptical/conical				Late Palaeocene	Partly igneous (differential compaction)	Dyke-fed volcanic vents or craters formed at the sea floor
Hodges *et al.* (1999)	3D seismic	FSB (T65/66/67)	Dome-shaped				Early Eocene	Igneous	Volcanoes
Davies *et al.* (2002)	3D seismic	FSB (T61/62)	Dome-shaped	1–1.7	50–300	5–16° (1°)	54–54.7 Ma	Igneous	Dyke-fed submarine volcanoes
Bell & Butcher (2002)	3D seismic	FSB (T67)	Dome-shaped with circular or elliptical shapes	<2	>100	<15° (4°)		Basaltic rock or heavily cemented clastic materials	Submarine hyaloclastite-dominated vents
Jamtveit *et al.* (2004), Svensen *et al.* (2004), Planke *et al.* (2005)	2D and 3D seismic; exploration well 6607/12-1; field studies	Møre and Vøring Basins; Karoo, South Africa	Eye-shaped, dome-shaped craters				Palaeocene–Eocene boundary (54–54.8 Ma); some Palaeocene in the Møre Basin	Dominantly sedimentary altered by hydrothermal fluids, some with magmatic component	Hydrothermal vents
Tranche 67 (Fig. 3a)	2D and 3D seismic	Northern Faeroe–Shetland Basin	Dome-shaped	0.8–1.3	90–195	9–16° (av. 12.5°)	Late Palaeocene	Sedimentary	
(Fig. 3b)			Dome-shaped	1.4–2.2	∼275	17–20°	Late Palaeocene–Early Eocene	Partly magmatic	
Tranche 4 (Fig. 4)	3D seismic	Central Faeroe–Shetland Basin	Dome-shaped	1–2.7	110–280	6–21° (av. 12.5°)	Palaeocene–Eocene boundary	Sedimentary (partly diagenetically altered and/or magmatic)	
Solsikke (Fig. 5)	3D seismic	Møre Basin (Solsikke)	Eye-shaped	0.5–1.2	60–225	9–26° (av. 20°)	Late Palaeocene–Early Eocene	Sedimentary	
(Fig. 6)			Dome-shaped	0.5–1.3	65–150	13–23° (av. 18°)	Late Palaeocene–Early Eocene	Sedimentary	
Tranche 38 (Fig. 7)	3D seismic	NE Rockall Basin	Dome-shaped	3–3.5	550–640	*c.* 20°	Late Palaeocene	Sedimentary	

upwards by a positive acoustic reflection of moderate acoustic impedance (TBFm) that is clearly onlapped. This reflection marks the Top Balder Formation and dates near the Palaeocene–Eocene transition. The base of the vent is coincident with a high-amplitude positive reflection (C). This reflection is interpreted to mark the top of a lava flow unit (Hansen 2004). The vent measures 2.2 km × 1.4 km, has a vertical relief of 270 m, and its flanks are inclined at *c*. 17° (compacted).

Central Faeroe–Shetland Basin

Three dome-shaped vents imaged by 3D seismic data from Tranche 4 (T4) of UK Quadrant 214 located in the central Faeroe–Shetland Basin are shown in Figure 4. These vents developed within the same stratigraphic interval (near the Palaeocene–Eocene transition; 54–54.7 Ma using Hardenbol *et al*. 1998) as similar structures described by Davies *et al*. (2002) *c*. 20 km to the north. The vents are delimited at their base by a low-amplitude negative reflection (BV) that shows a flat-lying concordant relationship with underlying stratal reflections. Upwards the vents are delimited by a moderate- to high-amplitude positive reflection (TV) that shows a subtle divergent relationship with the overburden. Often the TV reflection is offset by more than 10 m across the crest of the vents by polygonal faults that propagated downwards from the overlying Eocene section. The internal reflection configuration of vents V41 and V42 is chaotic, whereas V43 exhibits a bi-directionally downlapping internal geometry. A nearby vent exhibits a comparable organized internal reflection pattern, and from time-slices through this vent these are seen to have an 'onion-ring' geometry in planview similar to that illustrated by Davies *et al*. (2002).

The vents are linked to the underlying sill complex by vertical zones (pipes) of discontinuous seismic reflections that in some cases (e.g. underlying V41) exhibit slightly increased amplitudes. The seismic chimneys extend *c*. 1 km vertically and are a few hundred metres wide.

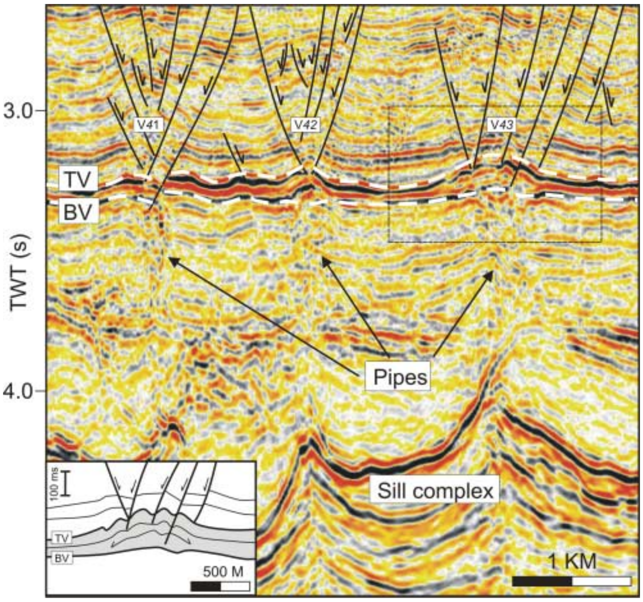

Fig. 4. Seismic cross-section from the T4 survey area located in the central Faeroe–Shetland Basin. Vent structures are seen above crests in the underlying sill complex. The crests of the vent structures are offset by polygonal faults that propagated downwards from the overlying Eocene strata. Bi-directional downlap is seen within vent V43 (inset). BV, base vent; TV, top vent.

Northeastern Møre Basin

Vents exhibiting two distinctively different cross-sectional geometries are imaged near the Palaeocene–Eocene boundary in the Solsikke case-study area located in the northeastern Møre Basin (Norwegian Quadrant 6403). The majority of the vents (*c*. 75%) are comparable in geometry with the dome-shaped vents described above from the Faeroe–Shetland Basin and these are not described in detail; rather the focus of this description is on a number of vents with eye-shaped cross-sectional geometries (Fig. 5). These vents are defined downwards by a locally discontinuous, low- to high-amplitude positive reflection, here referred to as the base vent reflection (BV), onto which well-defined internal vent reflections downlap. Underneath two of the vents (VS1 and VS3) the BV horizon truncates the underlying strata (e.g. horizon Z; Fig. 5a and b). VS2 does not exhibit a truncational base, but rather the BV reflection is deflected downwards, forming a downwarped concordant relationship with the immediately underlying strata (Fig. 5a and c). Two deeper, parallel and relatively continuous reflections of moderate amplitude (labelled W in Fig. 5a) do not appear to be affected by the downwarping underneath VS2. This indicates that the downwarped geometry of horizon Z is genuine and not an artefact, such as velocity push-down related to slow vent fill. The vents all have an organized internal geometry exhibiting a mounded bidirectionally downlapping reflection configuration. The uppermost downlapping reflection marks the upper boundary of the interval of accreted section and is interpreted as the top vent reflection (labelled TV in Fig. 5). The mounded geometry of the vents is reflected in the overlying strata (e.g. horizons X and Y).

VS1 and VS3 are located above the upper tips of faults that can be seen to offset the underlying strata (Fig. 5a and b). These faults penetrate to the deeper parts of the sill complex >2 km below. Elsewhere a vent is developed above the intersection between two fault sets, and other vents are linked to the underlying sill complex by pipe-like conduits of discontinuous seismic reflections (Fig. 6a), the circular planform of which is clearly imaged on variance slices through the seismic volume (Fig. 6b).

Northeastern Rockall Basin

Two exceptionally large vent structures, with estimated volumes of 1–2 km^3, have been mapped in Tranche 38 (T38, subset of the PGS MC3D NRT-96/97/98 survey) of UK Quadrant 164 located in the NE Rockall Basin (Fig. 7). Correlation with exploration well 164/27-1 situated in the survey area suggests that the top vent horizon (TV) is of Late Palaeocene age (J. Bagguley, pers. comm.). The first vent (V381) has a diameter of *c*. 3 km and covers an area of *c*. 6 km^2. The vent is 550 m high and has flank dips of *c*. 20° (compacted). The second vent (V382) is slightly larger than V38a, and has a diameter of 3.5 km and covers an area of 7.5 km^2. It is 640 m high and has present-day flank dips of *c*. 20°. The vents are circular in planview, and delimited downwards by a series of irregular and discontinuous high-amplitude reflections interpreted to form part of a lava flow unit (Hansen 2004). The vents have an overall chaotic internal reflection configuration, with the occasional cross-section showing a more organized mounded reflection configuration in the core of vent V382. The vents have a low-

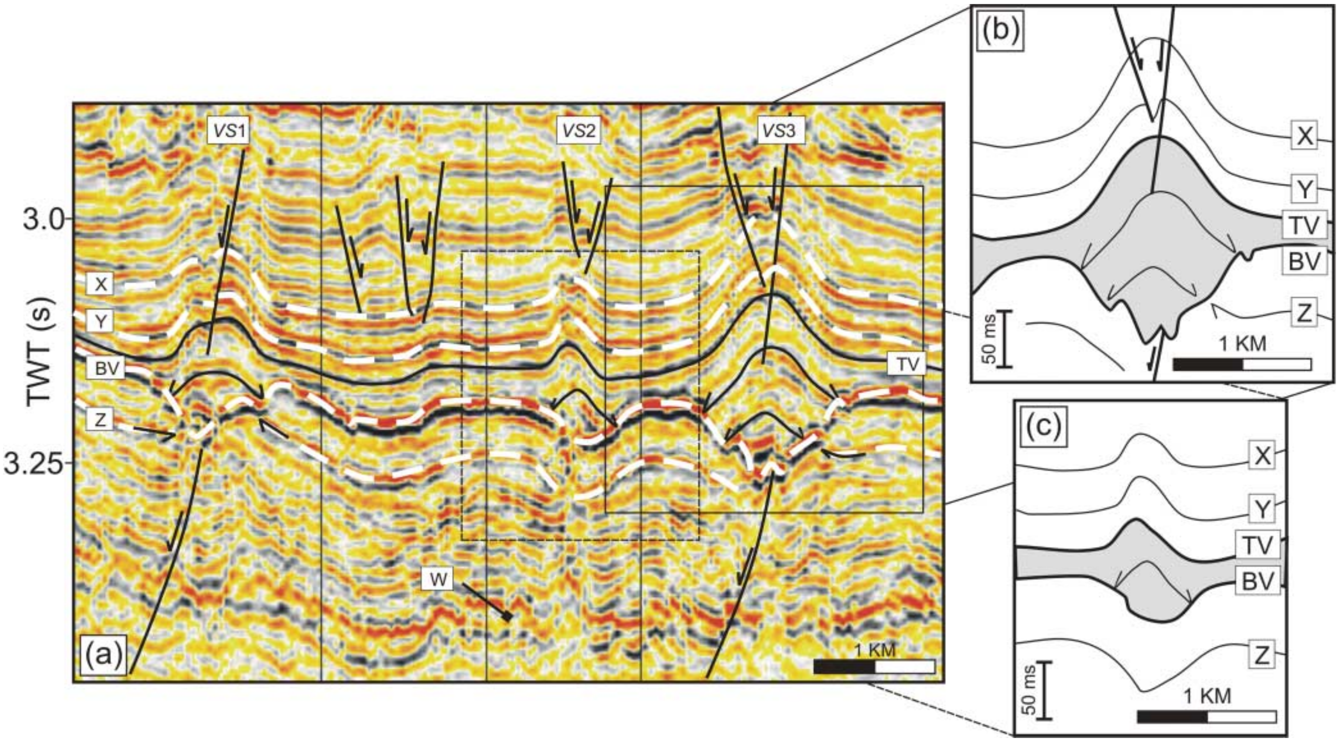

Fig. 5. (**a**) Seismic cross-section showing eye-shaped vent structures in the Solsikke survey area located in the northeastern Møre Basin. Vents VS1 and VS3 (**b**) are characterized by a truncational basal relationship and a concordant overburden relationship, whereas VS2 (**c**) is characterized by a downwarped concordant basal relationship and a concordant overburden relationship. VS1 and VS3 are developed above the upper tips of faults. BV, base vent; TV, top vent.

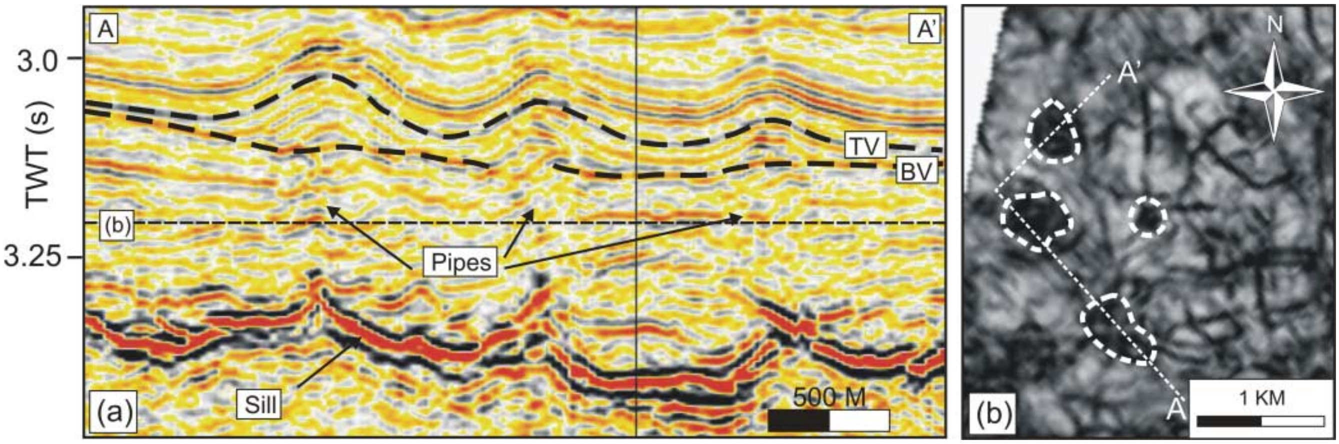

Fig. 6. (**a**) Seismic cross-section showing three conical vents in the Solsikke survey area. The vents are located above crests in an underlying sill to which they are linked by vertical zones (pipes) characterized by disrupted seismic reflections. BV, base vent; TV, top vent. (**b**) Map showing the variance attribute extracted along a time-slice between the sill and vents. The map shows the circular planview geometry of the pipes.

amplitude fill that shows poor impedance contrast with the overburden, making it difficult to map the upper boundary. However, the approximate upper boundary to the vents has been interpreted as a low-amplitude and discontinuous reflection (TV) on which some onlap terminations are seen. The overburden reflections show a slightly onlapping divergent pattern between the two vent structures with the section expanding away from the central axes of the vent structures towards the synform defined by the flanks of the two vents.

General characterization and origin of vent structures

Vent morphology

The seismic appearance of the upper and lower vent boundaries varies between 3D seismic surveys and between vents. Three geometric styles (dome-shaped, eye-shaped and craters) of comparable structures were recently recognized by Planke *et al*. (2005) based on their cross-sectional geometry. The terminology of Planke *et al*. (2005) is adopted here and the vent styles are

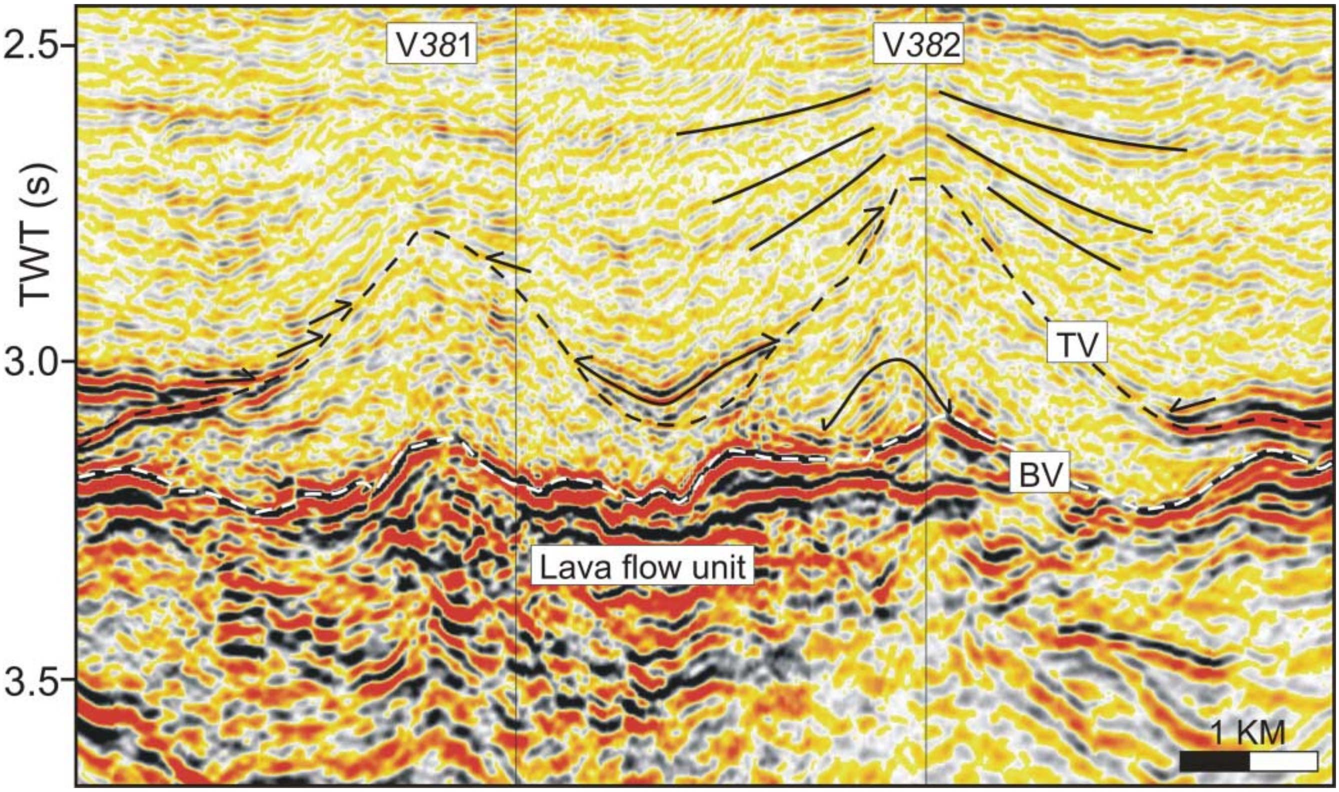

Fig. 7. Seismic cross-section from the T38 survey area located in the NE Rockall Basin showing the cross-sectional geometry of two large vent structures. The vents are formed above a lava flow unit and are clearly onlapped by overlying strata. The acoustic impedance of the mound fill is very similar to that of the surrounding strata and the vents generally have a chaotic internal geometry. However, on some vertical cuts through the vents they appear to include some internal bi-directionally downlapping reflections. Reflections within the overburden show a divergent configuration away from the crest of the vents. BV, base vent; TV, top vent.

further defined based on the detailed 3D seismic interpretation carried out in the case-study areas. A schematic summary of terminology is provided in Figure 8.

Dome-shaped vents are characterized by having a flat-lying base that is concordant with the underlying strata and an upward doming upper boundary. The upper boundary of a dome-shaped vents may be onlapped by overlying stratal reflections or exhibit a divergent to concordant relationship with these. Eye-shaped vents are delimited at their base by a concave-upward horizon that may show a concordant or truncational relationship with underlying stratal reflections. The eye-shaped vents are delimited upwards by upward doming surfaces that may be onlapped by overlying stratal reflections, or may have a divergent to concordant relationship with these. Craters have been identified on 2D seismic data from the Norwegian margin, but have not been observed in any of the 3D seismic case-study areas analysed here. They are characterized by a truncational basal relationship.

The vent structures, whether dome-shaped, eye-shaped or

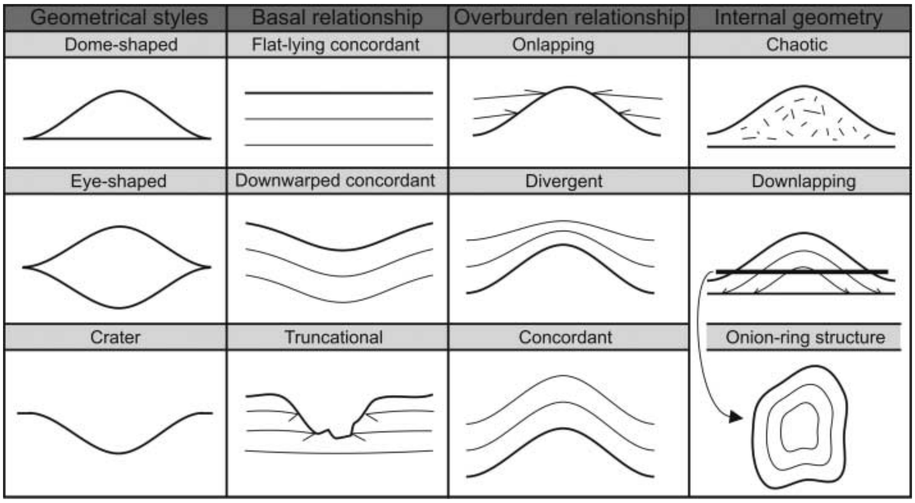

Fig. 8. Schematic illustrations of informal terminology used to characterize vent structures.

craters, are circular to slightly elongated in planform with more complex forms occasionally occurring as a result of amalgamation of two or more separate structures. Where continuous internal reflections are imaged within vents these are seen to parallel the upper vent boundary and give rise to an 'onion-ring' planview internal reflection pattern.

The geometric characteristics of vent structures within the case-study areas are summarized in Table 2 and from this some general quantitative characteristics are extracted. The vents range in diameter from 500 to 3500 m (mean 1350 m), in height between 50 and 640 m (mean 180 m), and have present-day compacted flank dips of 5–26° (mean of 16°) near their central axes, decreasing to a few degrees towards their margins. The volume of individual vents is of the order of *c*. 0.1–2 km^3.

Relationship with underlying sill complexes

The majority of the vent structures are spatially coincident with sill tips or crests in underlying sills, to which they are linked by vertical zones of disrupted seismic reflections. These zones may extend vertically for as much as 2.5 km and in some cases exhibit a slightly higher acoustic impedance than the surrounding strata. They are circular (Fig. 6b) to slightly elongated in planview and exhibit either pipe-like (Fig. 9a) or downward-tapering conical shapes (Fig. 9b). The chimneys do not extend upwards above the vents or downwards below the sills and it hence seems unlikely that they are seismic artefacts. Vents have also developed above the upper tips of faults that extend downwards to the deeper parts of the underlying sill complex (Fig. 9c) and at fault intersections.

Composition of vent fill

The clear spatial coincidence between the vent structures and underlying sill complexes suggests that the vents formed as a result of a common mechanism closely related to the emplacement of igneous sills. This has led previous workers to two possible interpretations of the vent structures as either hydrothermal sedimentary or volcanic in origin. Field-based studies of outcrop analogues in the Karoo, South Africa, suggest that the vent fill covers a spectrum from almost purely sedimentary to almost entirely composed of magmatic material (Gevers 1928; Jamtveit *et al*. 2004).

The only direct evidence for the composition of the vents is from exploration well 6607/12-1, which penetrates a vent structure and overlying mound structure in the Vøring Basin. The vent was found to be of hydrothermal origin (Svensen *et al*. 2003) and the overlying mound has been interpreted as a seep anomaly (Planke *et al*. 2005). An interpretation of the vents as sedimentary structures is supported by offsets of up to 10 m of the upper vent boundary by polygonal faults across the crests of vents in the Tranche 4 case-study area. Polygonal faulting is limited to fine-grained successions (Cartwright & Dewhurst 1998; Cartwright *et al*. 2003) and hence would not be expected to affect the vents if these were of magmatic composition. However, it would be premature to assume a hydrothermal origin for all vent structures based on this observation and well 6607/12-1 alone.

Davies *et al*. (2002) argued in favour of a magmatic origin for vent structures mapped in the central Faeroe–Shetland Basin. Their argument was based on two key pieces of evidence: (1) the acoustic impedance of the vents was high relative to that of the surrounding host-rock; (2) the vents exhibited an organized internal 'onion-ring' geometry. Further evidence in support of a magmatic origin arising from the case-study areas includes: (3) the preservation potential of the vents; (4) apparent differential compaction above some vent structures reflected in divergent overburden relationships. However, although the above observations are compatible with an interpretation of the vents as composed of magmatic material they are equally applicable to a sedimentary origin of the vents if these had been diagenetically altered by hydrothermal fluids. They are also compatible with an interpretation of the dome- and eye-shaped vents as carbonate mounds, but considering the evidence from well 6607/12-1 such an interpretation remains highly speculative.

Considering the seismic response from the vent structures in the case-study areas, where only limited acoustic impedance contrast is observed between the vent fill and the host-rock, it is most likely that the vent fill is sedimentary. Slightly increased acoustic impedance as seen in the central Faeroe–Shetland Basin examples (T4 case-study area; Fig. 4) could be indicative of either diagenetic alteration by hydrothermal fluids or the presence of magmatic material.

Interpretation of the vent plumbing system

The subvertical zones of discontinuous reflections that connect the vent structures with the underlying sill complex are either narrow (<1 km) and pipe-like (Fig. 9a) or have downward-tapering conical shapes (Fig. 9b).

The overall geometry of this latter style of plumbing system resembles that of diatremes described extensively in the mining literature over the last decade (e.g. Novikov & Slobodskoy 1979; Lorenz 1985). Diatremes are near-surface volcanic structures that form in response to a gaseous explosion and comprise a brecciated fill that is known to form the locus of many ore deposits (see Novikov & Slobodskoy 1979; Lorenz 1985). The funnel shape of diatremes can evolve from more pipe-like

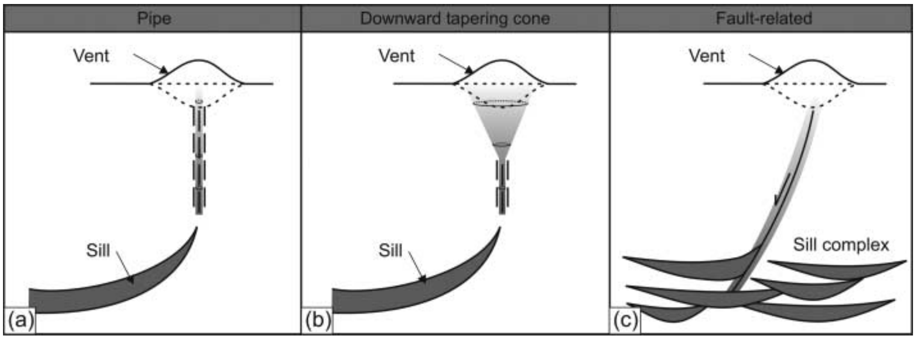

Fig. 9. Schematic illustration of different types of vent plumbing systems: (**a**) pipe-like; (**b**) downward-tapering cone; (**c**) fault-related.

conduits as a result of gas expansion and acceleration causing extensive downward-propagating sidewall erosion (Novikov & Slobodskoy 1979; Lorenz 1985). This suggests that the two types of vertical plumbing systems interpreted here are closely related mechanically and supports a hydrothermal origin of the vent fill.

The seismic interpretation shows that the pipes have the ability to cross-cut the thick mud-dominated Upper Cretaceous and Palaeocene sedimentary sequences found in volcanic basins along the NE Atlantic margin. This indicates that the fluid and steam pressure within the hydrothermal systems was sufficiently high to overcome the tensile strength of the overburden without utilizing pre-existing zones of weakness (e.g. polygonal faults) during upward migration. However, in the Solsikke survey area and elsewhere (Planke *et al*. 2005) vents are found above the upper tips of faults that penetrate to the deeper parts of the sill complexes several kilometres below (Fig. 9c). The location of vents above fault tips and fault intersections suggests that the faults in these places have acted as conduits for hydrothermal material. This is in agreement with other studies of fluid flow through fractured and faulted sedimentary sequences (Mayo 1958; Park & MacDiarmid 1970; Sibson 1996; Gartrell *et al*. 2003), and has also been recognized in studies of magmatic extrusions (Connor & Conway 2000) and intrusions (Hansen & Cartwright 2006).

Discussion: the timing of sill emplacement events along the NE Atlantic margin

Constraining the timing, duration and number of sill emplacement events in sedimentary basins constitutes a major challenge. This is linked to the fact that dates obtained from radiometric dating methods are often erroneous, yielding dating discrepancies of several million years (Jolley *et al*. 2002), because of alteration and poor sampling of sills penetrated by boreholes (Gibb & Kanaris-Sotiriou 1988). A new seismic-based technique that offers independent constraints on radiometric dating methods has recently been described by Smallwood & Maresh (2002), Trude *et al*. (2003) and Hansen & Cartwright (in press), who used post-intrusion sediment distribution and onlap relationships onto forced folds formed above igneous sills to constrain the timing of sill intrusion. Similarly, it has been suggested that the timing and duration of sill intrusion can be seismically constrained by dating the basal and upper boundaries of the intrusion-related vent structures described herein (Davies *et al*. 2002; Svensen *et al*. 2004; Planke *et al*. 2005). Importantly, seismic-stratigraphic dating of sill-related vent structures and forced folds allows for the relative timing of individual intrusive events to be constrained even when the seismic data are poorly correlated with well data as is the case in the case-study areas. Vents and/or intrusion-related forced folds developed at one stratigraphic level must logically predate similar structures formed at a stratigraphically shallower level and hence the latter must be associated with a later intrusive event.

Evidence of multiple sill emplacement events

The most significant result arising from this study is the identification of multiple emplacement events along the NE Atlantic margin (Table 2 and Fig. 10). For example, vent structures are developed at two stratigraphic levels within the T67 case-study area of the northern Faeroe–Shetland Basin (Figs 2 and 3), indicating two discrete episodes of sill intrusion. The majority of vents (>80%) are associated with the early (Late Palaeocene) phase and this event is further evidenced by the development of sill-related forced folding above two sills in the survey area (Hansen 2004). Evidence of multi-phase intrusion is also observed in the Tranche 38 case-study area of the NE Rockall Basin. In this area two vents developed during an early (Late Palaeocene) phase of intrusion (Fig. 7), whereas forced folding above eight sills (Hansen & Cartwright, in press) indicates a second (Early Eocene) phase. An example of the seismic expression of forced folding in the T38 case-study area and the relationship between the two identified intrusive events in the survey area are illustrated in Figure 11. In addition to the two intrusive phases directly identified within the T38 case-study area from the vents and the forced folds, respectively, evidence of an early (63–64 ± 0.5 Ma) episode of intrusion has been suggested based on recent ^{40}Ar/^{39}Ar dating of igneous sills in the 164/7-1 exploration well located *c*. 100 km north of the T38 survey area (Archer *et al*. 2005). This suggests that this area was affected by at least three discrete episodes of sill emplacement. Multiple emplacement events have previously been recognized in

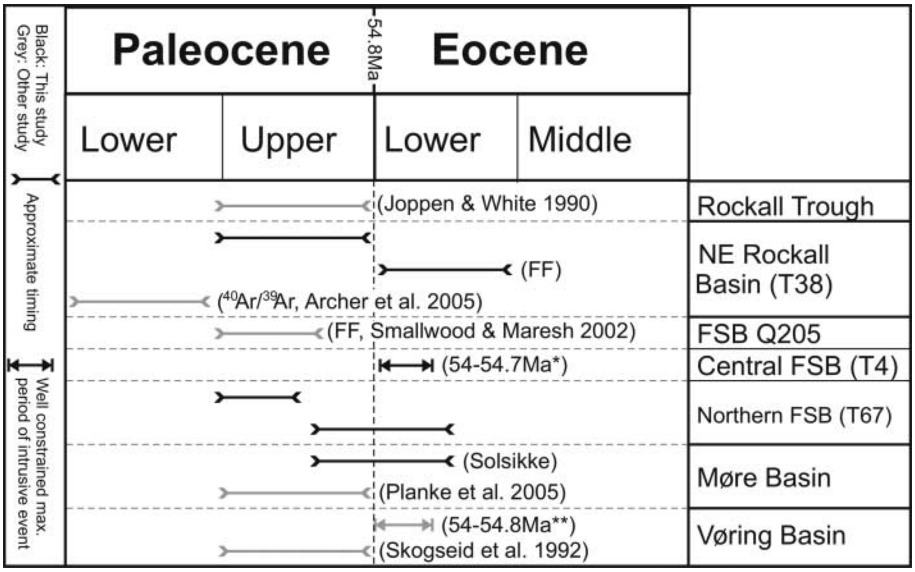

Fig. 10. Schematic time-line showing the relative timing of intrusive events in the case-study areas and other basins along the NE Atlantic margin. The diagram indicates that there were at least three phases of sill intrusion: an early phase during the Early Palaeocene, an intermediate phase during the Late Palaeocene, and a late phase near the Palaeocene–Eocene transition (54.8 Ma, Hardenbol *et al*. 1998). The timing of individual intrusive events is based on dating of vent horizons where nothing else is specified. FF, timing constrained from forced folding (Hansen & Cartwright in press). *Davies *et al*. (2002) and Trude *et al*. (2003). **Svensen *et al*. (2004) and Planke *et al*. (2005).

the Møre Basin, where *c*. 5% of the mapped vents are confined within the Palaeocene stratigraphy, indicating an earlier phase of intrusion than the main phase (95% of vents) near the Palaeocene–Eocene boundary (Svensen *et al*. 2004; Planke *et al*. 2005).

A major intrusive event near the Palaeocene–Eocene boundary has been documented on the Norwegian margin (Svensen *et al*. 2004; Planke *et al*. 2005) and in the central Faeroe–Shetland Basin (Davies *et al*. 2002; Trude *et al*. 2003) using seismic-stratigraphic techniques. Seismic correlation indicates that the vents mapped in the T4 case-study area are confined to the same stratigraphic interval and hence further supports the occurrence of a major intrusive phase near the Palaeocene–Eocene boundary. The later phase of intrusion in the T67 case-study area located in the northern Faeroe–Shetland Basin and vents in the Solsikke case-study area in the Møre Basin are also likely to be linked to this phase of intrusion, but this has still to be confirmed by detailed biostratigraphic correlation.

Uncertainty of seismic method for dating sill emplacement events

The uncertainty associated with seismic-based correlation of seismic reflections with well data has important implications for the accuracy of the emplacement ages and duration of emplacement events derived using the above technique. Using the time scale of Hardenbol *et al*. (1998) the major emplacement event near the Palaeocene–Eocene boundary can be constrained to 55.8–55 Ma and 55.7–55 Ma for the Norwegian margin (Svensen *et al*. 2004; Planke *et al*. 2005) and the central Faeroe–Shetland Basin (Davies *et al*. 2002; Trude *et al*. 2003), respectively. This suggests a possible maximum duration of this emplacement event of as much as 700–800 ka.

Expulsion of hydrothermal fluids and sediments triggered by sill intrusion occurs shortly after sill intrusion, probably while most of the sill is still molten (Jamtveit *et al*. 2004). Similarly, extrusion of sill-fed magmatic material would also require that the underlying feeder-sill was not solidified and was capable of acting as a conduit for the magma. This suggests that the vent structures must be formed within the time it takes from the feeder-sill being intruded until it has cooled, regardless of their composition. It has been proposed that the cooling time for a sill is proportional to the square of the thickness of the sill and it is estimated that even very thick sills (>300 m) would solidify within <10 ka (Jaeger 1961). The average sill imaged by 3D seismic data in the four case-study areas is estimated to be <100 m thick (Hansen 2004) and using the solidification equations derived by Jaeger (1961) it is estimated that these would be cooled within a few thousand years. This is significantly faster than any estimate derived from seismic interpretation, for which the minimum uncertainty is >100 ka. This minimum is probably the result of, and within the reasonable limitations of, uncertainties in the biostratigraphic dating and well correlation of the

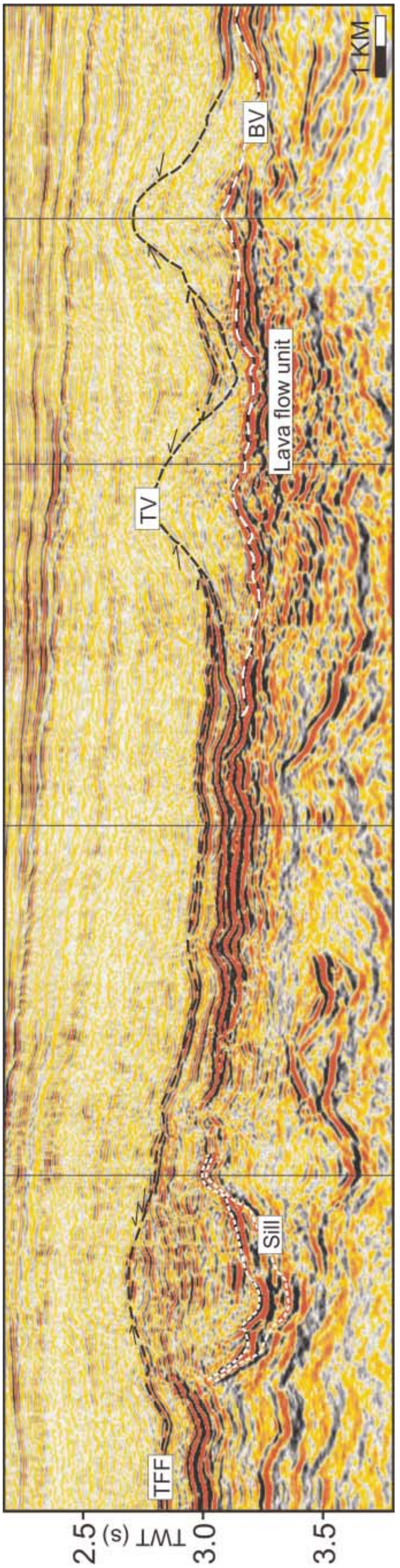

Fig. 11. Vertical seismic section showing evidence of multi-phase intrusion in the T38 survey area of the NE Rockall Basin. An early phase of intrusion during the Late Palaeocene is evident from the development of vent structures, whereas a later (Early Eocene) phase of intrusion is constrained by the onlap relationship onto an intrusion-related forced fold. The seismic horizon that marks the top of the forced fold (TFF) onlaps the vent structures, demonstrating the difference in the timing of the two intrusive episodes. BV, base vent; TV, top vent.

seismic reflections that represent the basal and upper vent boundaries.

The uncertainty in dating the timing and duration of sill emplacement events based on seismic interpretations means that even if vent structures are bound by the same seismic horizons it is impossible to establish synchronicity between the associated intrusions as multiple successive events may be confined within a single seismically constrained interval. For two separate emplacement events to be confidently distinguished based on seismic data alone they must be separated in time by an interval greater than the uncertainty in the dating of individual events and hence by more than 100 ka.

Implications for climate change studies

Sill intrusion into organic-rich sediments along the NE Atlantic margin causing explosive release of metamorphic thermogenic methane has recently been proposed as a triggering mechanism for initial Eocene global warming (Svensen *et al*. 2004). Critical to this hypothesis is that the intrusive igneous complexes of the Møre and Vøring Basins were emplaced at the Palaeocene–Eocene boundary within <20 ka coinciding with the Initial Eocene Thermal Maximum (IETM; Dickens 2004). In the following, two issues of concern related to such an interpretation are raised, and these will need to be addressed as part of the continuing efforts to establish the likelihood of a causative relationship between sill emplacement and climate change.

First, the onset of initial Eocene global warming is identified as a negative carbon and oxygen excursion in marine and terrestrial sediments, known as the IETM, and it has been linked to a massive and rapid (<20 ka) input of isotopically depleted carbon (Kennett & Stott 1991). If this input of isotopically depleted carbon was caused by sill intrusion, and hence that sill intrusion is the direct cause of the observed excursion in carbon and oxygen isotopes at the Palaeocene–Eocene boundary, each of the discrete intrusive events identified in the seismic data would be expected to have similar excursions associated with them. This is not the case, and this key observation clearly puts into doubt the existence of a causative relationship between sill emplacement and the IETM.

A second point of concern relates to the uncertainty in constraining the timing of sill intrusion based on vent horizons. This uncertainty has been shown to be an order of magnitude greater than the theoretically based estimate of the duration of the intrusive event itself. As a result, it is impossible, on the basis of seismic data alone, to infer whether one or several discrete short-lived (<10 ka) intrusive events took place during the time interval constrained by a related set of vent boundaries (>100 ka). This resolution problem could, as suggested by Svensen *et al*. (2004), be resolved by coring the Palaeocene–Eocene boundary strata on the flanks of individual vent complexes. However, without coring a large number of these along the full length of the NE Atlantic margin it would be impossible to constrain their age to a <20 ka interval, not to mention confidently linking this interval to the IETM.

Conclusions

(1) Vent structures with dome-, eye- and crater-shaped cross-sectional geometries are widespread in the Palaeocene–Eocene strata in sedimentary basins along the full length of the NE Atlantic margin. The vents have mean diameters of 1350 m, mean heights of 180 m, mean flank dips of 16° (present-day), and volumes of 0.1–2 km^2.

(2) The vents are associated with the intrusion of underlying sill complexes. They are commonly developed above sill edges and crests in sills to which they are linked by pipe- and diatreme-like structures. The vents also develop above the upper tips of deep-seated faults and at fault intersections.

(3) The vents are predominantly of sedimentary composition and may be partly diagenetically altered by hydrothermal fluids. Others are likely to include a magmatic component.

(4) The seismic-stratigraphic context of the vent structures can be used to constrain the timing of underlying sill intrusion with an uncertainty of *c*. 100–800 ka and to identify discrete episodes of intrusion separated by intervals greater than the uncertainty in dating individual events.

(5) Multiple episodes of intrusion occurred in the northern Faeroe–Shetland Basin (two episodes) and the North Rockall Basin (three episodes) during the Palaeocene–Eocene, indicating that magma emplacement occurred over a long period of time and during a minimum of three discrete episodes of intrusion along the NE Atlantic margin.

(6) The identification of multiple intrusive events within the North Atlantic Igneous Province during the Palaeocene and Eocene, and the uncertainty associated with seismic-based dating of intrusive events, puts into doubt the existence of a recently proposed causative relationship between sill emplacement and the Initial Eocene Thermal Maximum.

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