Tunnel valleys of the central and northern North Sea (56°N to 62°N): distribution and characteristics

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ABSTRACT

The analysis of buried tunnel valleys in the North Sea can provide information about the past configuration and dynamics of the Scandinavian and British ice sheets and the processes by which sediment and meltwater were transported at the ice-sheet base. However, little is presently known about the distribution and characteristics of tunnel valleys in the Norwegian sector of the North Sea. Here we use an extensive database of 3D seismic and high-resolution magnetic data to map more than 2200 tunnel valleys in the Norwegian and British sectors of the North Sea between 56°N and 62°N. With the exception of the deep Norwegian Channel, in which evidence for tunnel valleys is absent, the geological setting of the North Sea is interpreted to have been conducive to tunnel-valley formation and preservation because of its poorly consolidated substrate and shallow water depths. The highest density of tunnel valleys is located in the central part of the North Sea where Quaternary sediments are thickest. The extreme length of some of the tunnel valleys, which are up to 155 km long, supports theories that tunnel valleys form in stages rather than catastrophically. Detailed analysis of the orientation of tunnel valleys and their relative age relationships within four representative subareas shows that tunnel-valley orientation varies significantly across the central and northern North Sea and between different generations of valleys. This suggests that the pattern of subglacial meltwater drainage in the central and northern North Sea was different between each deglacial event in which tunnel valleys were formed, which is in contrast to the southerly meltwater drainage route that is indicated by the generally north-south orientation of tunnel valleys in the southern North Sea.

1. INTRODUCTION

Tunnel valleys are elongated and over-deepened depressions eroded by subglacial water flow into underlying sediments or bedrock under high water-pressure (Ó Cofaigh, 1996; Benn and Evans, 2010; Kehew et al., 2012; van der Vegt et al., 2012). Tunnel valleys start and terminate abruptly and are found buried and with surface expression, both onshore and offshore. They are often found in soft, poorly consolidated and low-permeable substrates such as mud, which are susceptible to erosion by water, but they can also appear in areas of harder substrate (Stackebrandt, 2009; Sandersen and Jørgensen, 2012). Tunnel valleys can reach lengths of more than 100 km, widths of up to 10 km and depths of 500 m (Ó Cofaigh, 1996; Praeg, 2003; Stackebrandt, 2009; van der Vegt et al., 2012). In plan-form, tunnel valleys are observed as individual straight or sinuous channels, and as complex anastomosing or dendritic networks (Praeg, 2003). A significant morphological characteristic of tunnel valleys is the presence of an undulating longitudinal profile, which is indicative of a subglacial origin by meltwater under pressure.

There are three main theories of tunnel-valley formation (Ó Cofaigh, 1996; Huuse and Lykke-Andersen, 2000; van der Vegt et al., 2012): (i) steady-state subglacial drainage of meltwater along hydrostatic pressure gradients; (ii) catastrophic meltwater discharge; (iii) direct glacial erosion with meltwater as the most important erosional agent. A combination of the above formation methods may also be considered, with evidence for complex formation over time and later alteration described by authors including Kristensen et al. (2007) and Stewart et al. (2013).

Pleistocene tunnel valleys are found in many areas of the formerly glaciated world, but have most often been reported from northern Europe and North America (Wright, 1973; Shaw and Gilbert, 1990; Piotrowski, 1997; Huuse and Lykke Andersen, 2000; Praeg, 2003; Stackebrandt, 2009; van der Vegt et al., 2012) where they formed beneath the ice sheets that existed during Quaternary glacial periods. Tunnel valleys can be important reservoirs for water or hydrocarbons (Huuse and Lykke-Andersen, 2000; Praeg, 2003), and can also contain shallow gas that can cause problems for seabed installations and hazards for drilling. The valleys also affect seismic imaging with depth due to the lithological variations of the infilled sediments.

Tunnel valleys are also described from ancient, pre-Quaternary ice ages. Many tunnel valleys were formed in the Late Ordovician, during the Hirnantian glaciation of northern Africa, about 445 Ma ago (Ghienne and Deynoux, 1998; Smart, 2000; Le Heron et al., 2004; Douillet et al., 2012). At that time, an ice sheet covered the entire continent from Morocco in the west to Saudi Arabia in the east. These ancient tunnel valleys are filled in by younger (Silurian) sands, which make them productive hydrocarbon reservoirs, and therefore they have been investigated and explored in considerable detail.

Generally, tunnel valleys are considered most likely to develop in the marginal, low-altitude zone of continental ice sheets, and have been linked to the production of surface meltwater that subsequently accesses the ice-sheet bed. Their axis direction is often described as perpendicular to the ice margin, and sub-parallel to the direction of past ice flow; for example, Praeg (2003) and Stackebrandt (2009) reported generally N-S trending tunnel-valley systems in the UK sector of the southern North Sea and in northern Germany and Poland, which were formed beneath the margin of the Elsterian Ice Sheet of marine isotope stage (MIS) 12. However, this is not always the case (e.g. Stewart et al., 2013).

In the North Sea, three generations of tunnel valleys have been recognised by many researchers, with each generation being correlated to one of the three last major glaciations on land in the surrounding countries (Ehlers and Linke, 1989; Wingfield, 1989, 1990; Kluiving et al., 2003). More recently, with the availability of 3D seismic data from the North Sea, the complex pattern of tunnel valleys has been mapped over a large area of the British sector, revealing that a threefold glaciation history of tunnel-valley formation was too simple. Kristensen et al. (2007) identified at least five tunnel-valley generations, whilst Stewart and Lonergan (2011) and Stewart et al. (2013) mapped up to seven generations of tunnel valleys. The oldest tunnel valleys were linked to the Elsterian Glaciation (MIS 12) based on the work of Toucanne et al. (2009), although this correlation has not been confirmed directly by sampling of tunnel-valley infill. The only previous study of tunnel valleys in the Norwegian sector of the North Sea was performed by Fichler et al. (2005), in which tunnel valleys in an area centred on 59°N, 2°E were mapped using 3D seismic cubes and high-resolution magnetic data, although no quantitative information on tunnel-valley dimensions or generations was provided.

In this study we map all the resolvable tunnel valleys in the Norwegian and British sectors of the North Sea north of 56°N, based on a large database of 3D seismic (>100,000 km^2) and high-resolution aeromagnetic data (Fig. 1). We analyse tunnel-valley morphology and establish a relative age relationship between the tunnel valleys in four representative subareas. The dimensions, orientations and density of the tunnel valleys are discussed in terms of the geological and glaciological controls on the formation and preservation of tunnel valleys in the central and southern North Sea and their implications for the routing of subglacial meltwater during regional deglaciation.

2. GEOLOGICAL BACKGROUND

The North Sea Basin has experienced significant deposition from the Jurassic onwards. During the Cenozoic, up to 3,000 m of sediments filled the central parts of the basin, resulting in subsidence along the basin axis (Gatliff et al., 1994). The basin, which extends towards the east into Germany and Poland, was gradually infilled by sediments during the Miocene/ Pliocene (Stackebrandt, 2009; Thøle et al., 2014). The British Geological Survey (BGS) undertook extensive regional mapping of the Quaternary stratigraphy of the entire British shelf during the 1970s and 1980s based on analogue 2D seismic lines and boreholes. In the central part of the North Sea, the lower part of the Quaternary basin was shown to have been infilled by relatively fine-grained deltaic sediments sourced from the east (Gatliff et al., 1994; Overeem et al., 2001). The lithology of the lower parts of the Quaternary northern North Sea Basin was suggested to contain mainly glacimarine to marine interglacial sediments, composed predominantly of sandy muds with some gravel and occasional sandy layers (Stoker, 1987; Johnson et al., 1993; Gatliff et al., 1994).

More recently, the availability of 2D and 3D seismic data from the North Sea has enabled detailed reconstructions of the evolution of the basin through the Quaternary (Lamb et al., 2017; Ottesen et al., 2018). In the northern North Sea (59-62ºN), the lower part of the Quaternary basin is infilled by a series of prograding sedimentary units (mainly glacigenic debris-flows originating from the delivery of subglacial sediment to the palaeo-shelf break) deposited from the east/southeast towards the west/northwest (Ottesen et al., 2014; Batchelor et al., 2017). The top of these units is cut by a prominent unconformity, which is termed the Upper Regional Unconformity (URU) (Moreau et al., 2012). In the east, the URU represents the base of the Norwegian Channel (Fig. 1), which was produced by erosion from the recurrent Norwegian Channel Ice Stream from around 1 Ma (Sejrup et al., 1995; Ottesen et al., 2014). West of the Norwegian Channel, the URU separates clinoforms deposited from the east and clinoforms sourced from the west.

In the central North Sea, a Quaternary sedimentary sequence up to 1,000 m thick filled in the deepest parts of the basin (Fig. 2) (Lamb et al., 2017; Ottesen et al., 2018). Sediment sources were mainly from the southeast by fluvial input as an elongated deltaic depocentre from the palaeo-Baltic river system. Some sediments were also sourced by the large European rivers such as the Rhine-Meuse and from the northeast (Norway) and west (UK) by fluvial/glacifluvial processes (Gibbard, 1988). In the central North Sea, the URU surface, which was originally mapped and extended from the northern North Sea, is represented as a conformity separating several relatively flat-lying units (Ottesen et al., 2014). Tunnel valleys appear mostly in these uppermost flat-lying units above the URU, which have a combined thickness of up to 300 m, but can also be eroded into the underlying sequences and sometimes, along the basin flanks, into lithified bedrock (Fig. 2).

The depositional environment of the Quaternary North Sea was complex and varied from subglacial to subaerial or proglacial, lacustrine or shallow marine. As water depth in the basin generally shallowed through the Quaternary, subaerial exposure linked to glacio-eustatic changes during Quaternary glaciations became more likely. Despite the use of industry 3D seismic data to interpret landforms on palaeo-surfaces within the stratigraphy of the basin (Stuart and Huuse, 2012; Dowdeswell and Ottesen, 2013; Ottesen et al., 2014, 2016; Lamb et al., 2016, 2017; Rose et al., 2016; Stewart, 2016; Batchelor et al., 2017; Reinardy et al., 2017; Rea et al., 2018), uncertainty still remains about the configuration, timing and extent of ice sheets in the North Sea. The relative stratigraphy of tunnel valleys been used to consider the total number of ice-sheet advances that have affected the basin during the Quaternary (Stewart and Lonergan, 2011), although a lack of absolute dates, complex tunnel-valley patterns, and a relatively poor understanding of the formation processes for tunnel valleys have made interpretation difficult. Most often, a conceptual model with an ice sheet covering the North Sea during the last three major glaciations (Weichselian, Elsterian and Saalian) are generally described, but this has been questioned by Stewart and Lonergan (2011), who found up to seven tunnel-valley generations potentially relating to MIS indicative of cold periods. Tunnel valleys provide unequivocal evidence of ice-sheet cover because they are formed subglacially. However, it is not clear exactly how generations of tunnel valleys relate to ice-sheet advances and readvances within a single glacial period. The extensive networks of buried tunnel valleys described by Stewart and Lonergan (2011), and others above, are generally found within stratigraphic layers that are younger than the Brunhes-Matuyama reversal event (780 ka) and older than the the Last Glacial Maximum (21 ka).

The identification of iceberg ploughmarks on horizons dated to older than 2 Ma in the southern and central North Sea (Dowdeswell and Ottesen, 2013; Rea et al., 2018) and glacigenic debris-flows on palaeo-slope surfaces close to the base-Quaternary in the northern North Sea (Ottesen et al., 2014, 2018; Batchelor et al., 2017) has pushed the glacial history of the North Sea Basin back to the beginning of the Quaternary. Although it is possible that some of these earlier glaciations resulted in tunnel-valley formation, most of the thousands of buried tunnel valleys that are preserved within the flat-lying sediment units above the URU

(Fig. 2) are younger than 1 Ma in age, by which time the North Sea Basin was mainly infilled (Ottesen et al., 2018).

3. DATABASE AND METHODS

Our study area comprises the Norwegian and British sectors of the North Sea north of 56°N (Fig. 1). We merged the mapping carried out by Lonergan et al. (2006), Stewart and Lonergan (2011) and Stewart et al. (2012) with extensive new mapping of tunnel valleys in the Norwegian sector of the North Sea. The boundary of the study area follows approximately the western limit of the 3D seismic cubes, whereas in the east the limit is set 10 to 20 km outside the Norwegian coastline close to the boundary between crystalline and sedimentary rocks (Fig. 1). To the north, the study area is bounded by the limit of the 3D seismic cubes at around 62°N. The study region has a total area of about 180,000 km^2.

3.1 3D seismic database

The PGS Megasurvey comprises most of the released 3D seismic reflection cubes of the Norwegian part of the North Sea (56°N-62°N) and many cubes in the British sector (Fig. 1). The Megasurvey is organised into rectangles, where individual 3D cubes have been merged and clipped inside each of the rectangles (Fig. 3a). Each rectangle is composed of many 3D cubes with variations in seismic acquisition directions (white lines in Fig. 3a).

The quality of the seismic data is variable across the merged dataset (e.g. Fig. 3b). As the 3D surveys were configured to image the subsurface at greater depths than examined here, the upper parts of the merged seismic data often display a poor signal to noise ratio, and the contrast in acoustic impedance between seabed and water column can cause disruption close to this interface (Fig. 3b). Data gaps are also visible. However, as in other studies (Lonergan et al., 2006; Kristensen et al., 2007; Lutz et al., 2009; Kristensen and Huuse, 2012; Moreau et al., 2012; Muther et al., 2012; Stewart et al., 2012, 2013), the ability to explore 3D seismic reflection data both vertically and horizontally allows comprehensive imaging of laterally complex features, such as tunnel valleys, across the region, even in the shallower sections of the 3D data.

The vertical sampling interval for the PGS Megasurvey is 4 ms, which provides a maximum vertical resolution. Horizontal resolution for the entire merged survey is 25 m, a considerable improvement on previous regional merged datasets in which the outlines of tunnel valleys could be observed but no further detail was visible (e.g. Stewart et al., 2013).

The Utstord cube, to the east of the PGS Megasurvey (AOI 2 in Fig. 1), has a horizontal resolution of 25 m and vertical sampling every 4 ms. Acquisition direction is NNW-SSE. Some additional 3D seismic cubes outside (or partly overlapping) the PGS Megasurvey are used, e.g. TA0701, NH0504, EGB 2005, NVG-10M. In total, *c.* 110 000 km^2 are covered by 3D seismic data.

3.2 High-resolution aeromagnetic data

During the Geological Survey of Norway's (NGU) Crustal Onshore-Offshore Project (COOP; Olesen et al., 2013), an updated airborne magnetic survey map was compiled from existing and new high-resolution magnetic data (Fig. 1). Approximately 82,000 km of new aeromagnetic data was acquired in the Norwegian North Sea (CNAS-10) in a regular line-tie-line configuration with 1 km line spacing and a sensor altitude of 115 m above sea-level. These data were merged with existing magnetic data from TGS (VGVG-96, Q-17 and the UHAM-09), which were acquired at a similar altitude but with denser line spacing of 200 to 250 m.

High-pass filtering was applied to the new magnetic data compilation to extract the magnetic signal from shallow sources and to highlight the signature of the tunnel valleys. The high-pass filtered data reflect the varying resolution of the different surveys, which is mainly related to acquisition parameters including flight altitude and profile distance. Increases in water depth and distance-to-magnetic source decrease the signal-to-noise ratio and can hamper channel identification.

3.3 Mapping of tunnel valleys

3.3.1 Seismic data

The 3D seismic cubes were inspected for tunnel valleys using mainly horizontal timeslices through the surveys in which tunnel-valley margins are well-imaged (Figs. 5 to 8). Initial screening for tunnel valleys was carried out from the seabed at intervals of 50 ms in timeslice, and the margins of the valleys were digitised using Petrel seismic interpretation software before being exported to ESRI ArcGIS.

From this initial reconnaissance, four Areas of Interest (AOI) were selected for closer inspection (Figs. 1, 5 to 8). Tunnel valleys within these areas were mapped in timeslices at 4 to 8 ms intervals, and using vertical seismic profiles, to capture details of their morphology. Further detailed measurements of individual tunnel-valley morphology (widths, lengths, direction) were performed in ArcMap using these digitised horizons. Circular statistical analyses and calculation of mean resultant directions were performed using the GeOrient software. All orientation measurements are presented as bidirectional because flow direction for tunnel-valley formation has not been consistently established.

In the four AOI (Figs. 5-8), cross-cutting relationships and geomorphological similarity between tunnel valleys, imaged in horizontal timeslices, were used to group the tunnel valleys into ‘generations’ considered to be of a similar age, as described in Stewart and Lonergan (2011) and Stewart et al. (2013). In AOI 1 and AOI 4, generational interpretations first described in Stewart and Lonergan (2011) and Stewart et al. (2013) were expanded further using the new PGS Megasurvey seismic data. Mean orientations were calculated for individual generations as above.

3.3.2 Magnetic data

State-of-the-art high-resolution magnetic data enable the identification of subtle magnetization contrasts both onshore and offshore. The only limiting factors are distance to the source and data density, which control the lateral resolution of the data. The disturbance and exchange of material can produce significant magnetic contrasts even in generally low magnetic sediments. Magnetic data are commonly utilised in archeology to identify buried ancient settlements; for example, former grabens and ditches for houses or palisades that have been buried by sediment often produce a regular pattern in magnetic data (e.g. Kvamme, 2003).

The same principle can be used, at a larger scale, to identify buried tunnel valleys in the offshore record (Fichler et al., 2005). There is a subtle but detectable magnetization contrast between the sediments that were eroded by subglacial meltwater to form a tunnel valley and the heterogenic infill of the valley. In addition, a secondary change in magnetic mineralogy may result from biological and chemical differences between the sediments. High-pass filtered magnetic data emphasise these contrasts and can resolve several generations of tunnel valleys at different depths.

In our aeromagnetic data, Quaternary tunnel valleys are imaged clearly as both positive and negative anomalies (Fig. 3c). At the first order, positive magnetic anomalies are likely to be produced where a tunnel valley is infilled by relatively coarse-grained sediment dominated by basement clasts that have a significantly higher magnetization compared to surrounding sedimentary rocks. Negative anomalies are probably produced where a tunnel valley is infilled by relatively fine-grained sand, silt and clay that have lower magnetization compared to the base and sides of the tunnel valley. Although the magnitude of these contrasts is typically small, because quartz-dominated fine-grained sediments commonly show low magnetization, state-of-the-art magnetometers and high-density data acquisition enable channels with this type of infill to be mapped (Fig. 3c).

Where no seismic data are available (Fig. 1), we interpreted channel features from the magnetic data only. Although the mapping of tunnel valleys based solely on magnetic data might not detect the entire system, the aeromagnetic data provide an overview of the distribution of the channels (Fig. 4). It can be difficult to differentiate tunnel valleys from other source anomalies, including pipelines, cables and sub-crops of sedimentary layers. In addition, channels that display a relatively straight geometry can appear similar to data artefacts, particularly where a potential channel has a similar orientation to the direction of data acquisition. To avoid over-interpretation of magnetic lineaments in our analysis of the high-pass filtered magnetic data, the dendritic or slightly meandering shape of magnetic anomalies (Fig. 3c) was used as a character identifier of tunnel valleys.

Overall, we identify several cross-cutting channel systems from the magnetic data (Fig. 4). Where both types of data are available, we find the use of seismic and magnetic data to detect tunnel valleys to be well-correlated (Fig. 9).

4. RESULTS

4.1 General distribution and morphology

A total of 2297 tunnel valleys were mapped across an area of approximately 150,000 km^2 in the British and Norwegian sectors of the North Sea; 2158 tunnel valleys in 3D seismic data, and 139 in the magnetic surveys only (Fig. 4). The tunnel valleys have a combined length of more than 33,000 line-km. All of the tunnel valleys are between 0.5 and 10 km wide and tens to hundreds of meters in depth, which is consistent with nearby studies compiled by van der Vegt et al. (2012) and Stewart et al. (2013).

Some of the valleys have surface expression, and are known from bathymetric surveys (i.e. Stewart, 2016), but most described here are buried. The majority of the tunnel valleys are imaged between the seabed and around 600 ms two-way travel time (TWT), equivalent to around 400 m beneath the seabed using sediment velocities of 1700 to 1900 m/s (Graham, 2007; Ottesen et al., 2014). A map of tunnel-valley density, which was calculated using the mapped valleys in both the seismic and magnetic datasets, shows that the highest density of tunnel valleys is in the center of the study area at around 1.7°E, from 59°N to 59.2°N, although this is partly reliant on data coverage and quality (Fig. 10). Buried tunnel valleys are observed north of 61°N, which has not been reported previously in the North Sea. Although this area is covered by our magnetic dataset, no tunnel valleys are reported from within the Norwegian Channel (Figs. 4 and 10).

The most striking geomorphological observation from our new regional cross-border dataset is the length of the buried tunnel valleys; the longest feature is measured at 155 km, and this is limited by data extent (Fig. 11). To our knowledge, this is the longest tunnel valley observed in the North Sea to date. Two other buried tunnel valleys are measured at >100 km in length, and several valleys are observed with lengths of 80 to 100 km (Fig. 11). It is likely that these measurements are underestimating true lengths, partly due to data extents, and also because areas of poor data quality within the merged 3D datasets preclude the correlation of valleys between regions (Figs. 4 and 10).

As observed in previous works (Lonergan et al., 2006; Kristensen et al., 2007; Lutz et al., 2009; Stewart and Lonergan, 2011; Muther et al., 2012; Stewart et al., 2013), the complex system of tunnel valleys mapped across the North Sea comprises numerous overlapping systems that can be separated into a number of 'generations' of varying age. Below, we describe the morphology and generational interpretation of tunnel valleys in more detail for AOI 1 to 4 across the study area (Figs. 5-8).

4.2 Area of Interest 1

AOI 1 is situated in the southern part of the study area from 56.45°N, 2.12°E to 57.21°N, 3.08°E (Fig. 1). The total study area is 4500 km^2. From the PGS Megasurvey 3D seismic data, we identified fifteen valleys that could be well-defined and/or mapped within the interpretation software (Fig. 5). Many of the valleys appear to extend outside the study area, although some shorter valleys begin and terminate within the AOI and have lengths of around 25 to 30 km.

AOI 1 extends the area interpreted as 'Dataset M' in Figure 9 of Stewart et al. (2013), enabling the additional tunnel valleys that we observe here to be analysed in the generational framework outlined by those authors. Five cross-cutting generations of tunnel valleys are observed in AOI 1 (Fig. 5). Weighted orientation measurements (Table 1) show that the two oldest sets of tunnel valleys generally trend NE-SW while the youngest three sets display a pronounced NW-SE preferred orientation. Of note in AOI 1 is the large set of NW-SE trending youngest valleys (Generation 5, pink in Fig. 5), which display anastomosing sections and clearly cross-cut older generations (Fig. 5d). The largest of these valleys extends beyond AOI 1 and reaches a length of up to 155 km (Fig. 11).

4.3 Area of Interest 2

AOI 2 is defined by the Utstord 3D seismic reflection cube, which is located in the transition zone between the North Sea Plateau and the Norwegian Channel west of Stavanger from 58.47°N, 3.12°E to 59.41°N, 3.59°E (Fig. 1). The seismic cube covers an area of 5285 km^2. Of this, *c.* 2900 km^2 (57 %) covers the North Sea Plateau, and the rest the Norwegian Channel (Fig. 6b). Many of the valleys within AOI 2 appear to terminate towards the flank of the Norwegian Channel (Fig. 6b). Although tunnel valleys are not generally identified within the channel itself, a few valleys extend onto its western margin (Fig. 4).

Around 25 tunnel valleys were identified within AOI 2, although only 6 clearly cross-cut one another; these were interpreted as forming 5 generations (Fig. 6b and c). Some of the older valleys are clearly incising from a lower stratigraphic level than the youngest (Fig. 6d). The defining characteristic of the AOI 2 tunnel valleys, including those not included in the generational framework (grey in Fig. 6), is their general NE-SW trend, with only a few valleys, in Generations 1 and 3, displaying a more preferred NNE-SSW and NNW-SSE directionality, respectively (Fig. 6b and c, Table 2). Given the relatively low number of valleys that cross-cut one another in this AOI, overall patterns of directionality in the generational interpretation (summarised in Table 2) are not considered to be as significant as in some other areas. However, the NE-SW trend of the majority of the valleys may be related to their proximity to the Norwegian Channel, which is discussed further in Section 5 of this paper.

AOI 2 includes part of the >50 km-long buried channel system that has been mapped previously by Reinardy et al. (2017) (‘R’ in Fig. 6b) and interpreted by them as an Early Pleistocene fluvial channel because of its meandering form. We map this channel on both 3D seismic and magnetic data, and interpret it to be part of a much larger tunnel valley system that extends for more than 100 km from the western margin of the Norwegian Channel towards the south-west (Fig. 4). We interpret this channel as a tunnel valley on account of its size and regional geological context. First, with a depth of more than 200 m and a width of up to 2 km, the dimensions of this channel are compatible with a tunnel valleyorigin beneath an ice sheet. Secondly, if the channel were fluvial, this would imply that water drained subaerially from the northeast to the southwest in the central North Sea. However, this area was the last part of the North Sea Basin to have been infilled during the Early Pleistocene and the coastline was probably located much further to the north during this time (Ottesen et al., 2014, 2018).

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4.4 Area of Interest 3

AOI 3 is situated in the north-eastern part of the study area from 60.09°N, 1.53°E to 60.71°N, 2.04°E (Fig. 1). The total study area is 2460 km^2. From the PGS Megasurvey 3D seismic data, 9 tunnel valleys are relatively well-imaged, although data quality in this area is comparatively poor (Fig. 7a). Five cross-cutting generations of tunnel valleys are identified (Fig. 7b). Many of the valleys appear to extend beyond the AOI boundary; the two large N-S trending tunnel valleys, which are assigned to Generations 3 and 4, are >80 km in length (Fig. 7b). The N-S directionality of these two tunnel valleys (Table 3) appears to be quite unusual across the whole study area, but is more common north of 60°N (Fig. 4).

4.5 Area of Interest 4

AOI 4, which is located in the western part of the study area within the UK sector of the North Sea Plateau from 58.06°N, 0.61°W to 58.61°N, 0.28°E (Fig. 1), has a total area of 3090 km^2. From the PGS Megasurvey 3D seismic data, we identified 23 well-defined tunnel valleys that could be mapped in the interpretation software and placed within a generational context (Fig. 8). Almost all of the valleys appear to extend beyond the study area (Fig. 8b).

AOI 4 extends the northern study area interpreted in Figure 9 of Stewart et al. (2013) to the west. As in Stewart et al. (2013), we find 7 generations of cross-cutting buried tunnel valleys in this AOI. Tunnel-valley orientations are summarised in Table 4, with the oldest generations, 1 to 3, showing a preferred NNE-SSW orientation. Generations 5 and 7 show a NE-SW trend, while generations 4 and 6 are less strongly oriented (Fig. 8c).

5. DISCUSSION

This study shows that buried tunnel valleys are present extensively across the British and Norwegian sectors of the central and northern North Sea, extending eastwards to the western margin of the Norwegian Channel (Fig. 4). In agreement with previous research in smaller study areas (van der Vegt et al., 2012; Stewart et al., 2013), the tunnel valleys can be separated into several cross-cutting generations (Figs. 5-8). Below, we discuss a number of points from this new work.

5.1 Tunnel-valley generations

Five generations of cross-cutting tunnel valleys are described in AOI 1 to 3, and seven in AOI 4 (Figs. 5-8), which is consistent with the findings of other similar studies (Lonergan et al., 2006; Kristensen et al., 2007; Lutz et al., 2009; Stewart and Lonergan, 2011; Muther et al., 2012; Stewart et al., 2013). The complexity of the tunnel-valley systems, combined with gaps in data coverage and areas of low data resolution, meant that it was not possible to link these generations across the whole study area. The increased complexity and higher number of generations in AOI 4 may reflect the higher density of tunnel valleys in this area (Fig. 10 and section 5.3 below).

Without further dating of material from the buried tunnel valleys and their surrounds, it is not possible to associate individual tunnel-valley generations with particular North Sea glaciations or cold periods; it is uncertain whether the different generations of tunnel valleys were formed during relatively short-lived fluctuations of the ice margin or during major deglacial events. This study finds that there are stratigraphic gaps between generations of tunnel valleys, particularly between tunnel valleys assigned to generations 1 and 2 and younger generations (e.g. Fig. 5c), although this interpretation is hampered somewhat by the erosive nature of glaciations and tunnel-valley formation, and the resolution of the seismic data. The tunnel valleys are separated by only a few tens of milliseconds of stratigraphy in seismic data, often relatively close to the seabed where reflections can be disturbed (Fig. 3b), making it difficult to consistently distinguish erosive surfaces. To advance further in our understanding of the formation and geometry of tunnel valleys requires higher-resolution seismic data and the acquisition of material for use in dating techniques. Although high-resolution site survey data are available to better image tunnel-valley fill, these types of surveys are generally only collected over small areas (up to several km^2) and it is difficult to extrapolate interpretations from such data across networks of tunnel valleys that stretch for tens to hundreds of kilometres.

5.2 Geometry

Around 84% of the tunnel valleys mapped from 3D seismic and magnetic data are < 20 km in length, and around 15% of the tunnel valleys are between 20 and 100 km long (Fig. 11), although many are observed to extend out with data limits, which affects overall summaries of tunnel valley lengths. Five of the tunnel valleys have lengths of greater than 100 km; three examples of these tunnel valleys are highlighted in Figure 11a. These three valleys trend approximately S-N or SSE-NNW from 56°N to 58°N, and have a curved geometry that is convex to the west. Tunnel valley b extends into AOI 1 where it is interpreted as part of Generation 5, the youngest set of tunnel valleys in the AOI (Fig. 5). Tunnel valley a can also be interpreted to extend into AOI 1 (red dashed lines), which would further increase its reported length and permit its classification as Generation 5. The directionality of these long valleys is markedly different to those of the older Generation 1 and 2 valleys in AOI 1, which generally trend NE-SW (Fig. 5c). We note that our measurements of tunnel-valley length are probably minimum estimates; many tunnel valleys extend beyond the data coverage, and areas of poor data quality within the 3D merged datasets may preclude the correlation of valleys between regions (Figs. 4 and 10).

The extreme length of the longest tunnel valleys reported in this study (Fig. 11) emphasises their importance in the glacial landscape and their role in ice-sheet drainage. The excavation and filling of such large valleys clearly requires a significant amount of water. We find that the geometry of these large tunnel valleys adds to the body of evidence that the North Sea and NW European tunnel valleys generally formed in stages over time rather than catastrophically (Kristensen and Huuse, 2012; Stewart et al., 2013).

5.3 Tunnel-valley density and distribution

The highest density of tunnel valleys within the study area, as observed from both the seismic and magnetic datasets (Fig. 10a), generally corresponds to the central, deepest part of the Quaternary North Sea Basin that contains the thickest Quaternary sediments (Fig. 10b) (Ottesen et al., 2014). This finding is in agreement with previous works that have found that tunnel-valley density typically increases where sediment thickness is greater (Stackebrandt, 2009; Stewart et al., 2013). This pattern is likely to be a consequence of both the greater preservation potential of geomorphological features in areas of thicker sediment, and a propensity for tunnel valleys to be formed where relatively erodible sediments are present.

Here we find that, although tunnel-valley density generally correlates to Quaternary sediment thickness, the areas of highest tunnel-valley density are located slightly to the north of the thickest Quaternary sediments, at around 59°N (Fig. 10). This is partly related to data availability; for example, relatively isolated 3D seismic datasets increase density measurements around the areas marked ‘A’ and ‘B’ in Fig. 10. However, the good data coverage around 59°N, where density is greatest, is of interest. In general, Quaternary sediment thickness in this area is greater than 500 m, and the highest density of valleys appears to roughly follow the north-northeast trending palaeogeography of the Quaternary basin (Lamb et al., 2017; Ottesen et al., 2018). The comparatively low density of tunnel valleys identified from the magnetic data to the north and north-west of Denmark (Fig. 10a) may be related to the presence/depth of the Cretaceous bedrock in this area, which is relatively close to the seabed (Nielsen et al., 2008).

The high density of tunnel valleys at around 59°N (Fig. 10a) could also be related to the glacial history of the central North Sea, which has been interpreted to have had a longer history of coverage by grounded ice compared with the southern North Sea (Buckley, 2012; Ottesen et al., 2018; Rea et al., 2018). Our interpretation of the channel that had been mapped previously as an Early Pleistocene fluvial channel (Reinardy et al., 2017) (Fig. 6b) as a subglacially formed tunnel valley adds to a body of work that suggests that a grounded ice sheet extended into the central North Sea Basin during the Early Pleistocene, prior to the incision of the Norwegian Channel (Buckley, 2012; Rose et al., 2016; Reinardy et al., 2017; Rea et al., 2018).

Commented [SMA2]: But don't we state in the intro that we think the valleys are genereally younger than 1Ma, when the Norwegian channel formed 1.1Ma?

The geological setting and glacial history of the North Sea Basin have clearly been conducive to the formation and preservation of thousands of tunnel valleys, particularly over the past *c.* 1 Ma since the basin became infilled (Ottesen et al., 2018). During the Mid- to Late Pleistocene, the combination of a shallow sea (< 300 m deep), which was partly subaerial during glacio-eustatic low sea-levels during glacial periods, a relatively mild climate during deglaciations producing huge amounts of meltwater, and a suitable substrate (generally poorly consolidated muds and sands), made the region favourable for tunnel-valley formation. This study finds that tunnel valleys are also present in the northern part of the North Sea above 61°N, less than 100 km from the present-day shelf edge (Figs. 4 and 10).

An exception to the generally high density of tunnel valleys across the North Sea is in the Norwegian Channel (Figs. 4 and 10). Although tunnel valleys are mapped at the western margin of the Norwegian Channel, we do not identify any tunnel valleys within the channel itself. This could be because this region has experienced extensive erosion during the full-glacial periods of the Mid- to Late Pleistocene, which removed evidence of older tunnel valleys, and/or because few tunnel valleys were formed beneath the Norwegian Channel Ice Stream, perhaps because of the significant water depths within the channel. The favourable setting of the North Sea Basin for tunnel-valley formation and preservation is in strong contrast to the mid-Norwegian continental shelf (62°N-68°N), where very few tunnel valleys have been identified (Rise pers. comm.). The relative absence of tunnel valleys from the mid-Norwegian margin is probably a consequence of the deeper continental shelf (150-500 m) and harder substrate of this area.

5.4 Tunnel valleys and ice margins

A schematic model for the maximum extent and early deglaciation of the Scandinavian and British ice sheets during the LGM (MIS 2), Saalian (MIS 6) and Elsterian

(MIS 12) glaciations is shown in Figure 12. During each of these three glaciations, an ice sheet covered the entire North Sea Plateau and reached the southern North Sea between Britain and the Netherlands (Ehlers et al., 2011; Hughes and Gibbard, 2018; Lang et al., 2018). To the north, the ice-sheet margin reached the shelf edge beyond Norway and Scotland (Sejrup et al., 2005, 2016; Bradwell et al., 2008; van der Vegt et al., 2012).

Previous studies partly constrain most reported buried tunnel valleys in the central and northern north Sea as being younger than the Brunhes-Matuyama reversal event at 780 ka and older than the LGM (Stewart and Lonergan, 2011; Stewart et al. 2013). Although little is known about the internal dynamics or deglacial pattern of the ice sheets during the pre-LGM glaciations, (for example, during the Saalian (MIS 6) and Elsterian (MIS 12)), the Norwegian Channel Ice Stream has been suggested to have collapsed and retreated rapidly from the shelf break along the Norwegian Channel following the Last Glacial Maximum (LGM) (Sejrup et al., 2016), which is probably linked to ingress of water from the north. Deglaciation of the Norwegian Channel during earlier glacial periods would also isolate the retreating Scandinavian Ice Sheet from the remnant ice sheet over the North Sea Plateau and Britain, as shown in our schematic model (Fig. 12). The down-wasting of an ice dome over the North Sea Plateau could explain the pattern of subglacial drainage towards the Norwegian Channel that is suggested by the orientation of some of the tunnel valleys in the central North Sea (Figs. 4 and 6). The existence of an ice dome that down-wasted over the subaerial North Sea Plateau during some deglaciation events could also explain the high density and variable orientation of the tunnel valleys in the study area; compared to tunnel valleys formed relative to a more stable or long-lasting ice-sheet to the south, tunnel valleys formed beneath a decaying ice dome would be controlled by more local factors. Recent models of subglacial drainage patterns, such as Lelandais et al. (2016), show increased complexity of tunnel valley patterning related to lobe geometries, for example.

Commented [SMA3]: This depends on the Norwegian channel being present during these older glaciations as well – which I think is correct, but we should specify when above

In contrast to tunnel valleys in the southern North Sea and northern Germany, which display a relatively consistent orientation that suggests subglacial drainage towards the south (grey arrows in Fig. 12) (Kluiving et al., 2003; Praeg, 2003; Stackebrandt, 2009; van der Vegt, 2012), the orientations of the different generations of tunnel valleys from our four AOI in the central and northern North Sea (Figs. 5-8) do not show any obvious overall directionality (Fig. 12). The changing orientation of tunnel valleys across the four AOI, and between generations, suggests that the pattern of subglacial meltwater drainage was different between each deglaciation or ice-retreat event in which the tunnel valleys were formed. This could, for example, reflect the shifting position of an ice divide or ice dome over the North

Sea Plateau (relatively distal to more stable ice margins to the south) between successive deglaciations, which would route water in different directions depending on the local morphology of the ice-sheet surface after break-up. This kind of variability in tunnel valley geometries, potentially reflecting changing ice sheet margins during different glacial periods, can also be seen in the comparison of surface (LGM) and buried tunnel valleys by Stewart (2016).

6. CONCLUSIONS

- We use a combination of 3D seismic data and airborne magnetic data to map, for the first time, the distribution of more than 2200 tunnel valleys in the British and Norwegian sectors of the central and northern North Sea. We find a strong correlation between the location of tunnel valleys derived from magnetic data and 3D seismic cubes.
- Our broad data coverage permits the identification of several tunnel valleys of extreme length. The longest tunnel valley is 155 km long, and several other valleys have lengths of > 80 km. The significant amount of water required to excavate and fill these valleys adds to the body of evidence that tunnel valleys generally form in stages over time rather than catastrophically.
- Tunnel valleys are mapped at the western margin of the Norwegian Channel yet are not identified within the channel itself. It is possible that tunnel valleys were not formed within the Norwegian Channel because of early rapid deglaciation of the Norwegian Channel Ice Stream following glacial maxima, which would have been encouraged by the significant water depths of the channel. Evidence for tunnel valleys may also have been removed by extensive ice-stream erosion during the Mid- to Late Pleistocene.
- To the west of the Norwegian Channel, the North Sea is interpreted to have been favourable for tunnel-valley development because of the poorly consolidated substrate and shallow (< 200 m) water depths of the North Sea Plateau, which would have been partly subaerial during Mid- to Late Pleistocene glacio-eustatic sea-level lowstands. The down-wasting of an ice cap centered over the North Sea Plateau could explain the high density and variable orientation of tunnel valleys in the central and southern North Sea, as well as the pattern of subglacial drainage towards the Norwegian Channel that is suggested by the orientation of some of the valleys.

- The highest density of tunnel valleys generally corresponds to the central, deepest part of the Quaternary North Sea Basin, suggesting a link between sediment thickness and the formation and/or preservation of tunnel valleys.
- Five generations of tunnel valleys are reported from three AOI in the central and northern North Sea, whilst seven generations are interpreted from a fourth AOI. Tunnel-valley orientation is shown to vary significantly between generations, suggesting that subglacial meltwater followed a different drainage pattern between ice-retreat events. This is in contrast to the relatively consistent N-S orientation of tunnel valleys in the southern North Sea and northern Germany, which indicate a generally southerly meltwater drainage route.

7. ACKNOWLEDGEMENTS

We acknowledge AkerBP for permission to use their seismic database and workspace to carry out the seismic work in this study. We thank TGS for permission to use their magnetic data and to present a regional 2D seismic line. We also thank PGS for permission to publish data from the PGS Megasurvey and Searcher Seismic for access to the Utstord 3D seismic cube. Add any funding sources. CLB was in receipt of a Norwegian VISTA post-doctoral scholarship during this work.

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FIGURE CAPTIONS

Figure 1. Location map of the study area in the northern and central North Sea, showing the distribution of the 3D seismic data and aeromagnetic data used in this work. Dark blue lines are national boundaries. AOI = Area of interest.

Figure 2. Regional 2D seismic line across the North Sea Basin (NW-SE) showing the distribution of tunnel valleys within the Quaternary stratigraphy, provided by TGS. Light and dark blue areas show Early Quaternary deltaic units deposited mainly from the east. Red areas represent sediments deposited from west. Green areas are the sediment units that infilled the last part of the central North Sea Basin during the Early Pleistocene. Yellow areas are the generally flat-lying sedimentary units of Mid-Late Pleistocene age that were deposited above the Brunhes-Matuyama palaeomagnetic boundary. Tunnel valleys (white fill) generally occur within this uppermost package. Image adapted from Ottesen et al. (2018).

Figure 3. (a) Time-slice (100 ms depth) of four rectangles of the PGS Megasurvey, showing how the individual 3D seismic surveys have been merged and arranged into a regular framework. White parallel lines show the seismic line acquisition directions within the different cubes. Location is in Fig. 1. (b) Seismic profile showing the variable quality of the data within the merged 3D cubes. (c) Map of the magnetic data, showing how tunnel-valley infill can be characterised by both positive and negative magnetic anomalies.

Figure 4. The distribution of tunnel valleys in the northern and central North Sea as mapped in this study using 3D seismic data (black lines) and aeromagnetic data (red lines). Dark blue lines are national boundaries.

Figure 5. (a) Seismic time-slice through the tunnel valleys in AOI 1 in the central North Sea. (b) Interpretation of the five generations of tunnel valleys shown in (a). (c) Rose diagrams showing the orientation of the different generations of tunnel valleys. Colours are the same as in (a) and (b). (d) Seismic profile through some of the tunnel valleys in AOI 1.

Figure 6. (a) Seismic time-slice through some of the tunnel valleys in AOI 2 in the Norwegian sector of the central North Sea (Utstord cube). (b) Interpretation of the five generations of tunnel valleys shown in (a), together with the tunnel valleys that were not

assigned a generation (grey). R marks the location of the valley that was interpreted as a proglacial channel by Reinardy et al. (2017). (c) Rose diagrams showing the orientation of the different generations of tunnel valleys. Colours are the same as in (a) and (b). (d) Seismic profile through some of the tunnel valleys in AOI 2.

Figure 7. (a) Seismic time-slice through some of the tunnel valleys in AOI 3 in the northern North Sea. (b) Interpretation of the five generations of tunnel valleys shown in (a). (c) Rose diagrams showing the orientation of the different generations of tunnel valleys. Colours are the same as in (a) and (b).

Figure 8. (a) Seismic time-slice through the tunnel valleys in AOI 4 in the British sector of the central North Sea. (b) Interpretation of the seven generations of tunnel valleys shown in (a). (c) Rose diagrams showing the orientation of the different generations of tunnel valleys. Colours are the same as in (a) and (b). (d) Seismic profile through some of the tunnel valleys in AOI 4.

Figure 9. Example showing the mapping of tunnel valleys using magnetic data and 3D seismic data in the central North Sea. Location is in Fig. 1. (a) Map of the magnetic data. Light blue lines show those areas that are covered by both the 3D seismic and magnetic data. (b) Interpretation of tunnel valleys from 3D seismic and magnetic data where they are both available (black lines) and from magnetic data only where 3D seismic data is absent (green lines). The overlap between the black and green lines shows the strong correlation between the use of magnetic and 3D seismic data to detect tunnel valleys.

Figure 10. (a) Map showing the density of tunnel valleys in the central and northern North Sea, derived from 3D seismic and aeromagnetic data. The extents of the 3D seismic and magnetic datasets are shown by the white and red lines, respectively. Dark blue lines are national boundaries. Letters A and B denote examples of regions in which the availability of 3D seismic data probably partly explains the relatively high density of tunnel valleys. (b) Map showing the thickness of Quaternary sediments in the central and northern North Sea Basin, adapted from Ottesen et al. (2014).

Figure 11. Interpretation map showing the three longest tunnel valleys, valleys a, b and c, that have been identified in the central and northern North Sea. Location is in Fig. 1. Tunnel valley

b extends into AOI 1, where it was assigned to the youngest tunnel-valley generation - Generation 5 (Fig. 5). Red dashed lines show that tunnel valley a may also extend into AOI 1. Inset shows a histogram of the length of more than 2200 tunnel valleys in the central and northern North Sea. Note the logarithmic scale of the y-axis.

Figure 12. (a) Map showing the orientation of the different generations of tunnel valleys in the four areas of interest (AOIs) in the central and northern North Sea. Also shown is the maximum extent of the European Ice Sheet during the LGM (dark blue line), MIS 6 (Saalian Glaciation; light green line), and MIS 12 (Elsterian Glaciation; orange line), derived from Hughes and Gibbard, 2018. Tentative ice-sheet configurations during the last deglaciation are shown by the dashed black lines with purple fill. Coloured arrows show tunnel-valley orientations as reported in this study. Note that the different generations of tunnel valleys are not correlated between the four AOIs. Grey arrows show the dominant tunnel-valley orientations reported from the southern North Sea and north-west Europe (van der Vegt, 2012). Red and white outlines show the extent of the aeromagnetic and seismic data used in this study, respectively. The dark green outline is the western margin of the Norwegian Channel. (b) Profile showing the present-day topography across the central North Sea, from Scotland to southern Norway. Hypothesised ice-sheet configurations during the last deglaciation are shown by the dashed lines with purple fill.

TABLES

AOI	Generation	Mean Resultant Direction (°)
1	All	117-297
1	1 (oldest)	044-224
1	2	073-253
1	3	152-332
1	4	113-293
1	5 (youngest)	126-306

Table 1. Tunnel-valley orientation measurements for AOI 1 by generation.

AOI	Generation	Mean Resultant Direction (°)
2	All (plus no gen.)	052-232
2	No gen.	054-234
2	1 (oldest)	022-202
2	2	081-261
2	3	149-329
2	4	023-203
2	5 (youngest)	078-258

Table 2. Tunnel-valley orientation measurements for AOI 2 by generation.

AOI	Generation	Mean Resultant Direction (°)
3	All	002-182
3	1 (oldest)	111-291
3	2	090-270
3	3	012-192
3	4	176-356
3	5 (youngest)	056-236

Table 3. Tunnel-valley orientation measurements for AOI 3 by generation.

AOI	Generation	Mean Resultant Direction (°)
4	All	033-213
4	1 (oldest)	037-217
4	2	020-200
4	3	014-194
4	4	165-345
4	5	070-250
	6	130-310
	7 (youngest)	051-231

Table 4. Tunnel-valley orientation measurements for AOI 4 by generation.