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Tunnel valleys as geohazards: New insights from high-resolution 3D seismic data

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ABSTRACT:

High-resolution 3D seismic data are used to analyse the infill of buried tunnel valleys in the North Sea. The level of detail provided by the high-resolution three-dimensional seismic data (6.25 m bin size, ~4 m vertical resolution) represents a step-change in our ability to investigate the internal architecture of tunnel valleys and their role as geohazards. We discover that over 40 % of the tunnel valleys examined contain buried glacial landforms including eskers, crevasse squeeze ridges, glacitectonic structures, and kettle holes. Due to the association of these features with shallow gas, the tunnel valleys which contain them have implications as geohazards for shallow drilling and infrastructure installation efforts.

1 Introduction

Tunnel valleys are large (kilometres wide, hundreds of metres deep) channels incised into bedrock and sedimentary sequences in many formerly glaciated landscapes. They are formed by water flowing under pressure beneath ice sheets, particularly during deglaciation, and can offer unique insights into how water affects ice-sheet flow under extreme melt conditions (Kirkham et al., 2022). Tunnel valleys are also important reservoirs of water, ore minerals and hydrocarbons; their variable infill can produce difficulties when interpreting seismic profiles of the subsurface (Kristensen and Huuse, 2012; Frahm et al., 2020) and sometimes contains shallow gas accumulations which represent hazards to drilling and increases the risks associated with installing seabed infrastructure (Lohrberg et al., 2020; Ottesen et al., 2020). Obtaining a complete understanding of the processes responsible for tunnel valley formation is also important when planning the locations of deep geological repositories for nuclear waste in regions which may become glaciated again in the future (Iverson and Person, 2012; Beaud et al., 2016).

Despite over a century of research, tunnel valleys remain relatively enigmatic glacial features because very few modern analogues for them exist beneath extant ice sheets. Furthermore, the resolution of 3D seismic reflection datasets used to examine their infill in the past has been too coarse to adequately image their internal structures. In this paper, we apply high-resolution 3D seismic data, originally acquired by energy companies in the North Sea, to image the internal structures of tunnel valleys in unprecedented detail and discuss their implications as geohazards.

2 Methodology

High-resolution 3D seismic data, originally acquired for the assessment of geohazards such as shallow gas, were used to conduct a detailed examination of the infill and internal architecture of tunnel valleys buried beneath the seafloor of the central North Sea. The acquisition system comprised two 1200 m long streamers towed 3 m beneath the sea surface. Each streamer had 96 hydrophone groups at 12.5 m spacing, a 6.25 m shot interval and a 1 ms sample rate. The seismic source consisted of two 4 × 40 inch^3 (2.62 L) sleeve airgun clusters, fired in flip flop formation, with a signal frequency range between ~20–250 Hz (Games, 2012).

This acquisition system is particularly well suited for assessing the infill of shallow buried tunnel valleys as precise GPS positioning and laser tracking of the streamers permit data to be binned at high resolution. In addition, the long length of the streamers enables improved velocity analyses to be conducted. The resulting velocity data can be used in a range of processes to suppress seismic multiples, which can be prominent in data from formerly glaciated continental shelves such as the North Sea (Games, 2012; Games and Wakefield, 2014; Games and Self, 2017).

Data processing was conducted using ProMAX 3D software and included swell noise attenuation, tide correction, multiple suppression using a combination of SRME, SRWEMA and radon transform methods (all modelled and subtracted), two passes of velocity analysis run at 250×250 m intervals, normal moveout correction and bandpass filtering (20–250 Hz).

The final processed datasets consist of time migrated 3D stacks with a 1-ms sample rate, a 6.25×6.25 m bin size and a vertical resolution of ~4 m, given the 100–125 Hz dominant frequency of the seismic-reflection data (Kallweit and Wood, 1982). However, in practice, where reflections are coherent, the data may detect features as small as 0.5 m high along individual reflectors (King, 2020; Kirkham et al., 2021). The final processed seismic data were analysed using S&P Global Kingdom Software. Seven high-resolution 3D seismic datasets, covering a combined area of ~67 km^2, were analysed in this study.

3 Results and discussion

We image 19 cross-cutting incisions in the high-resolution 3D seismic data, which we interpret as tunnel valleys formed by subglacial meltwater based on their distinctive morphology (e.g., Stewart et al., 2013). These tunnel valleys record meltwater erosion over the last ~800,000 years as multiple ice sheets grew and deglaciated over the United Kingdom and Western Europe in a cyclic fashion (Huuse and Lykke-Andersen, 2000; Stewart and Lonergan, 2011; Ottesen et al., 2020; Clark et al., 2022b).

Inspection of the internal architecture of the tunnel valleys demonstrates that over 40 % contain smaller glacial landforms including eskers, crevasse-squeeze ridges, glacitectonic structures, kettle holes and braided channel structures buried within the larger structures (Figure 1; Kirkham et al., 2021). The landforms imaged using the high-resolution 3D seismic data represent the first time that many of these features have been observed inside tunnel valleys in either terrestrial or marine environments (Kehew et al., 2012; van der Vegt et al., 2012). Consequently, glacial landforms, both erosional and depositional in nature, are likely far more common inside tunnel valleys than previously recognised.

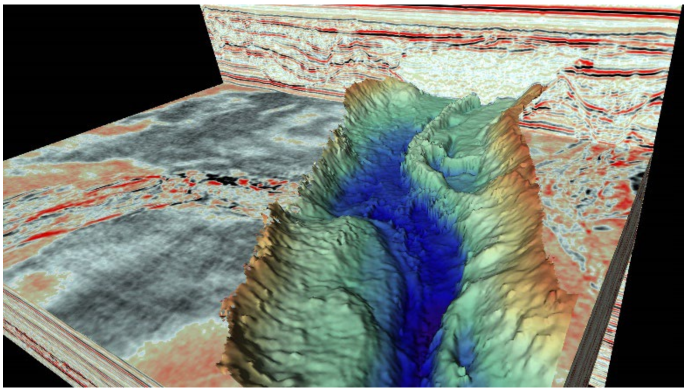

Figure 1. An esker containing shallow gas mapped within a tunnel valley using high-resolution 3D seismic data. The mapped horizon in the image is approximately 1 km wide.

The landforms are most commonly present within larger tunnel valleys (wider than ~400 m and deeper than ~75 m), particularly in the deepest ones, and typically occur within valleys characterised by more complex infill patterns. In addition, many of the landforms contain shallow gas accumulations. These gas accumulations generally occur within older tunnel valley generations, potentially indicating that the shallower sediments covering the younger tunnel valley generations might be an ineffective stratigraphic trap for shallow gas.

We do not observe instances of gas migration from beneath the valleys into their internal structures, which may suggest that the gas is biogenic. However, as our datasets are small in planimetric area, it may be possible that gas migration could have occurred upwards from outside of the dataset boundaries and then spread laterally along the landforms contained within the tunnel valleys. Greater data coverage would help to assess the likelihood of this hypothesis. Regardless of the origin of the gas, the extensive length (>14 km) and continuity of many of these landforms means that they potentially represent a hazard for seafloor installations and may reduce the efficiency of carbon capture and storage efforts in areas where tunnel valleys are present (Figure 2).

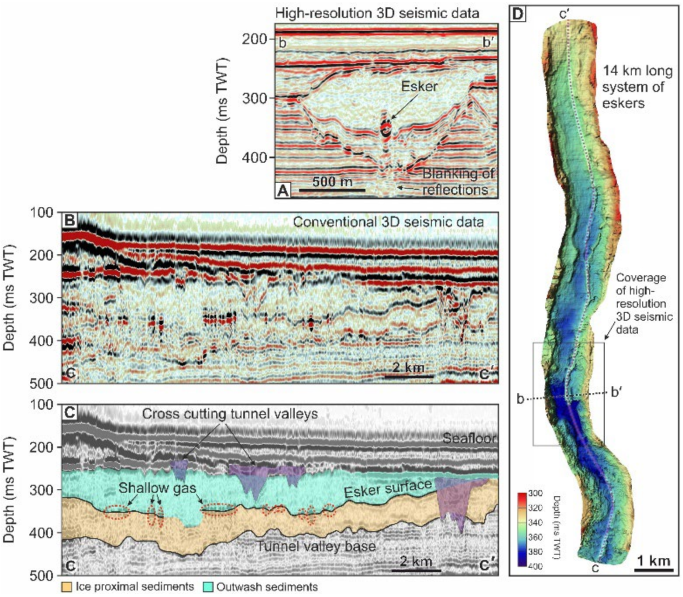

Figure 2. Gas-charged eskers buried within tunnel valleys. (A) Cross-section of a tunnel valley in high-resolution 3D seismic data containing an esker characterised by a high-amplitude seismic reflection with phase-reversed polarity over the ridge crest. (B) Seismic profile along the length of the esker using conventional 3D seismic data, interpreted in (C). Stippled red lines indicate the locations of shallow gas anomalies. (D) Mapped seismic horizon in the centre of the tunnel valley infill corresponding to the esker reflection in conventional 3D seismic data. A 14-km long system of eskers can be visualized.

Whilst the infill architecture of these tunnel valleys remains complex, in accordance with previous studies (e.g., Cameron et al., 1987; Praeg, 1996; Huuse and Lykke-Andersen, 2000; Kluiving et al., 2003; Praeg, 2003; Kristensen et al., 2007; Kristensen et al., 2008; Lutz et al., 2009; Stewart et al., 2012; van der Vegt et al., 2012), advances in the resolution of 3D seismic-reflection data permit some subtle patterns to be drawn out which were unresolvable in past investigations. The new high-resolution 3D seismic data show that the overall pattern of tunnel valley infill in the North Sea records decreasing ice sheet influence towards the top of the tunnel valleys and reflects the retreat of the ice-sheet margin away from the features after they are incised. At a more subtle level, the infill of earlier (older) tunnel valley generations reflects sedimentation during relatively gradual ice-sheet retreat with occasional episodes of overriding by re-advancing grounded ice. In contrast, tunnel valleys formed in more recent glaciations are characterised by greater variability in their sedimentation patterns which reflects dynamic fluctuations of the margins of these later ice sheets, including readvances and stagnation, during valley filling and ice retreat.

4 Conclusions

The step-change in resolution offered by high-resolution 3D seismic data provides unprecedented insight into the internal architecture of buried tunnel valleys in the North Sea. Smaller landforms of glacial origin are commonly buried within the tunnel valleys. Many of these landforms are undetectable at the resolution of conventional 3D seismic surveys but, due to their association with shallow gas, may hazards to shallow drilling and infrastructure installation efforts. The continuity of some of these glacial landforms buried within the tunnel valleys may also provide preferential pathways for subsurface fluid flow, which has implications for the efficacy of carbon capture and storage efforts in previously glaciated terrains like the North Sea. Directions for future work should include expanding the assessment of tunnel valleys over broader spatial scales, tracing the impacts of the valleys on existing infrastructure projects, and further investigation of the origin of the gas found within the landforms and whether this is capable of migrating though the valleys and the other landforms that they contain. Owners of suitable datasets are encouraged to contact the authors if they wish to pursue this investigation further!

5 References

Beaud, F., Flowers, G. E., and Venditti, J. G. (2016). Efficacy of bedrock erosion by subglacial water flow. Earth Surface Dynamics, v. 4, no, 1, 125-145, https://doi.org/10.5194/esurf-4-125-2016.

Cameron, T. D. J., Stoker, M. S., and Long, D. (1987). The history of Quaternary sedimentation in the UK sector of the North Sea Basin. Journal of the Geological Society, v. 144, 43-58, https://doi.org/10.1144/gsjgs.144.1.0043.

Clark, C. D., Ely, J. C., Hindmarsh, R. C. A., Bradley, S., Ignéczi, A., Fabel, D., Ó Cofaigh, C., Chiverrell, R. C., Scourse, J., Benetti, S., Bradwell, T., Evans, D. J. A., Roberts, D. H., Burke, M., Callard, S. L., Medialdea, A., Saher, M., Small, D., Smedley, R. K., Gasson, E., Gregoire, L., Gandy, N., Hughes, A. L. C., Ballantyne, C., Bateman, M. D., Bigg, G. R., Doole, J., Dove, D., Duller, G. A. T., Jenkins, G. T. H., Livingstone, S. L., McCarron, S., Moreton, S., Pollard, D., Praeg, D., Sejrup, H. P., Van Landeghem, K. J. J., and Wilson, P. (2022). Growth and retreat of the last British–Irish Ice Sheet, 31 000 to 15 000 years ago: the BRITICE-CHRONO reconstruction. Boreas, https://doi.org/10.1111/bor.12594.

Frahm, L., Hübscher, C., Warwel, A., Preine, J., and Huster, H. (2020). Misinterpretation of velocity pull-ups caused by high-velocity infill of tunnel valleys in the southern Baltic

Sea. Near Surface Geophysics, https://doi.org/10.1002/nsg.12122.
Games, K. P. (2012). Shallow gas detection - why HRS, why 3D, why not HRS 3D? First Break, v. 30, 25-33, https://doi.org/10.3997/1365-2397.2012016.
Games, K. P., and Self, E. (2017). HRS 3D data — a fundamental change in site survey geohazard interpretation. First Break, v. 35, no, 2152, https://doi.org/10.3997/1365-2397.2017008.
Games, K. P., and Wakefield, N. D. (2014). The successful design, development and acquisition of a UHRS 3D seismic dataset, Near Surface Geoscience: Athens, Greece, https://doi.org/10.3997/2214-4609.20142132.
Huuse, M., and Lykke-Andersen, H. (2000). Overdeepened Quaternary valleys in the eastern Danish North Sea morphology and origin. Quaternary Science Reviews, v. 19, 1233-1253, https://doi.org/10.1016/S0277-3791(99)00103-1.
Iverson, N., and Person, M. (2012). Glacier-bed geomorphic processes and hydrologic conditions relevant to nuclear waste disposal. Geofluids, v. 12, no, 1, 38-57, https://doi.org/10.1111/j.1468-8123.2011.00355.x.
Kallweit, R. S., and Wood, L. C. (1982). The limits of resolution of zero-phase wavelets. GEOPHYSICS, v. 47, no, 7, 1035-1046, https://doi.org/10.1190/1.1441367.
Kehew, A. E., Piotrowski, J. A., and Jørgensen, F. (2012). Tunnel valleys: Concepts and controversies — A review. Earth-Science Reviews, v. 113, no, 1-2, 33-58, https://doi.org/10.1016/j.earscirev.2012.02.002.
King, E. C. (2020). The precision of radar-derived subglacial bed topography: a case study from Pine Island Glacier, Antarctica. Annals of Glaciology, 1-8, https://doi.org/10.1017/aog.2020.33.
Kirkham, J. D., Hogan, K., Larter, R. D., Arnold, N., Ely, J. C., Self, E., Games, K., Huuse, M., Stewart, M., Ottesen, D., and Dowdeswell, J. A. (2022). Tunnel valley formation beneath deglaciating mid-latitude ice sheets: Observations and modelling. Quaternary Science Reviews.
Kirkham, J. D., Hogan, K. A., Larter, R. D., Self, E., Games, K., Huuse, M., Stewart, M. A., Ottesen, D., Arnold, N. S., and Dowdeswell, J. A. (2021). Tunnel valley infill and genesis revealed by high-resolution 3-D seismic data. Geology, v. 49, no, 12, 1516-1520, https://doi.org/10.1130/g49048.1.
Kluiving, S. J., Bosch, J. A., Ebbing, J. H., Mesdag, C. S., and Westerhoff, R. S. (2003). Onshore and offshore seismic and lithostratigraphic analysis of a deeply incised Quaternary buried valley system in the Northern Netherlands. Journal of Applied Geophysics, v. 53, no, 4, 249-271, https://doi.org/10.1016/j.jappgeo.2003.08.002.
Kristensen, T. B., and Huuse, M. (2012). Multistage erosion and infill of buried Pleistocene tunnel valleys and associated seismic velocity effects. Geological Society, London, Special Publications, v. 368, no, 1, 159-172, https://doi.org/10.1144/sp368.15.
Kristensen, T. B., Huuse, M., Piotrowski, J. A., and Clausen, O. R. (2007). A morphometric analysis of tunnel valleys in the eastern North Sea based on 3D seismic data. Journal of Quaternary Science, v. 22, no, 8, 801-815, https://doi.org/10.1002/jqs.1123.
Kristensen, T. B., Piotrowski, J. A., Huuse, M., Clausen, O. R., and Hamberg, L. (2008). Time-transgressive tunnel valley formation indicated by infill sediment structure, North Sea – the role of glaciohydraulic supercooling. Earth Surface Processes and Landforms, v. 33, no, 4, 546-559, https://doi.org/10.1002/esp.1668.
Lohrberg, A., Schwarzer, K., Unverricht, D., Omlin, A., and Krastel, S. (2020). Architecture of tunnel valleys in the southeastern North Sea: new insights from high-resolution seismic imaging. Journal of Quaternary Science, https://doi.org/10.1002/jqs.3244.
Lutz, R. K., Gaedicke, C., Reinhardt, L., and Winsemann, J. (2009). Pleistocene tunnel valleys in the German North Sea: spatial distribution and morphology. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, v. 160, no, 3, 225-235, https://doi.org/10.1127/1860-1804/2009/0160-0225.
Ottesen, D., Stewart, M., Brönner, M., and Batchelor, C. L. (2020). Tunnel valleys of the central and northern North Sea (56°N to 62°N): Distribution and characteristics. Marine Geology, v. 425, https://doi.org/10.1016/j.margeo.2020.106199.
Praeg, D. (1996). Morphology, stratigraphy and genesis of buried Mid-Pleistocene tunnel valleys in the southern North Sea Basin.. PhD thesis]: University of Edinburgh.
Praeg, D. (2003). Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin—high resolution from low frequencies. Journal of Applied Geophysics, v. 53, no, 4, 273-298, https://doi.org/10.1016/j.jappgeo.2003.08.001.
Stewart, M., Lonergan, L., and Hampson, G. (2012). 3D seismic analysis of buried tunnel valleys in the Central North Sea: tunnel valley fill sedimentary architecture, in Huuse, M., Redfern, J., Le Heron, D. P., Dixon, R., Moscariello, A., and Craig, J., eds., Glaciogenic Reservoirs and Hydrocrabon systems, Volume 368, Geological Society, London, Special Publications, p. 173-184.
Stewart, M. A., Lonergan, L., and Hampson, G. (2013). 3D seismic analysis of buried tunnel valleys in the central North Sea: morphology, cross-cutting generations and glacial history. Quaternary Science Reviews, 72, 1-17.
Stewart, M. A., and Lonergan, L. (2011). Seven glacial cycles in the middle-late Pleistocene of northwest Europe: Geomorphic evidence from buried tunnel valleys. Geology, v. 39, no, 3, 283-286, https://doi.org/10.1130/g31631.1.
van der Vegt, P., Janszen, A., and Moscariello, A. (2012). Tunnel valleys: current knowledge and future perspectives, in Huuse, M., Redfern, J., Le Heron, D. P., Dixon, R., Moscariello, A., and Craig, J., eds., Glaciogenic Reservoirs and Hydrocarbon Systems, Volume 368: London, Geological Society, Special Publications, p. 75-97.