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The Glaciogenic Reservoir Analogue Studies Project (GRASP) - An Integrated Approach to Unravel Genesis, Infill and Architecture of Tunnel Valleys Reservoirs

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SUMMARY

Tunnel galleys are common features in Palaeozoic glaciogenic succession in North Africa and Middle East and they are amongst the most challenging target for hydrocarbon exploration and developing drilling in these regions. Similarly, these buried valleys form important groundwater reservoirs in Quaternary glaciated areas and their nature and sediment composition is critical to drive a sustainable production strategy and assess their vulnerability. Seismic resolution however, often limits the understanding of channel valleys morphology, 3D geometry and internal reservoir distribution, thus increasing the risk associated with developing effectively these reservoirs. Therefore a analogue-based predictive stratigraphical and sedimentological model can help to steer drilling strategy and reduce uncertainties and associated risks. For this purpose the GRASP joint industry programme was established four years ago focusing on an integrated study of tunnel valley infill and architecture from the southern North Sea (UK and NL). The thorough examination of existing large subsurface and outcrop data set regarding the last 3 Pleistocene glaciations in NW Europe resulted in an improved understanding of tunnel valley genesis, sedimentary process and internal architecture. This learning can be used ultimately to improve our predictive capability when exploring and developing natural resources from these geological systems.

Introduction

Tunnel valleys are common geological features of glaciated regions; they are deep and over-deepened elongated depressions, up to 100 km long, 5 km wide and up to 400 m deep. They are commonly genetically related to subglacial erosional and depositional processes although most of the proposed genetic models are mainly based on inferred mechanisms from the sedimentological record and geomorphological data, due to the difficulty in observing subglacial erosion and deposition processes in modern environments (van der Vegt et al., 2012). The valleys are often filled with clastic deposits forming fining and thinning upwards sequences which are interpreted to be associated with glacial withdrawals. Several exceptions to the latter sequence however exist (van der Vegt et al., 2012) and a generic model of tunnel valley infill yet is far from established. The small number of outcrops studied to date refer mostly to ancient glacial deposits of Palaeozoic age (e.g. Ordovician, Carboniferous) and rarely to Quaternary deposits. As an example, the well known Scarborough Bluffs in Ontario, Canada of Quaternary age (Karrow, 1961), or the Ordovician Iherir Valley outcrops in Algeria (Beuf et al., 1971), the Gargaf Arch in Libya (Le Heron et al., 2004), the Cantabrian Range, Spain (Gutiérrez-Marco, 2010) and the spectacular exposures in Mauritania (Ghienne and Deynoux, 1998) in fact all show a large variety of facies both in terms of lateral and vertical stacking patterns (e.g. van der Vegt et al., 2012) which makes it difficult to establish universal rules which would allow us to predict with high degree of confidence the facies and their architecture in the subsurface. The latter is of critical importance when dealing with geological modelling of tunnel valleys which in several regions of the world form large reservoirs containing valuable natural resources, including hydrocarbon and groundwater (Huuse et al. 2012).

The goals of a recently completed joint industry project, the Glacial Reservoir Analogue Studies Project (GRASP), which has been carried out over the last 4 years by a University consortium (Delft University of Technology, University of Aberdeen and The University of Cambridge), were therefore to improve the understanding of tunnel valley genetic processes, morphological parameters and type of infill and sedimentary architecture. The results of this research programme will be used to assist E&P operators to drive their exploration and development activities on glaciogenic reservoirs.

Methods

In order to advance our understanding of tunnel valleys and related deposits (geometry, facies and architecture) the GRASP developed a three-pronged approach.

- 1) The first component of the project focussed on the high-resolution 3D seismic interpretation of southern North Sea (SNS) tunnel valleys. For this purpose access to the SNS 3D seismic MegaSurvey was kindly granted by PGS, which allowed us to map the entire Quaternary tunnel valley network in the area encompassed between England and The Netherlands. The Dutch Geological Survey (TNO) provided extensive datasets of individual 3D surveys for key areas of interest in addition to regional 2D lines crossing the entire southern North Sea. Access to site surveys, performed by operators in association with geotechnical investigation for platform or and pipeline installation provided us with higher resolution seismic imaging specifically the shallowest part of the Quaternary sequence.
- 2) The second component of the GRASP focused on the sedimentology and architecture of the tunnel valley termination-proglacial outwash transition zone. During this research part, we re-examined and re-assessed the sedimentological significance of a number of well known outcrops in key locations if NW Europe (e.g. East Anglia, England; central Finland; Denmark) which in the past have been genetically associated with tunnel valley/proglacial deposits. Comparison with similar features in North America (Ontario) was also carried out.
- 3) The third part of the GRASP programme was dedicated to improve the current capability of predicting the nature and geometries of sedimentary bodies contained within tunnel valleys by examining in detail the subsurface data set with the highest density of data points currently available.

This dataset was provided by the Geological Survey of Hamburg State, Germany and include about 1000 boreholes with mud-logs, e-logs and cuttings from a relatively confined area (ca. 750 km²), which combined with available shallow seismic enabled us to reconstruct deterministically the sand body geometries and define their spatial relationships and 3D architecture.

Results

The detailed seismic interpretation of the complex Quaternary tunnel valley network occurring in the southern North Sea indicate that the infill of the tunnel valleys is usually divided into three seismic units and two lithostratigraphic units (Moreau et al., 2012). The base of the valleys is correlated with the glaciogenic Swarte Bank Formation of Elsterian age (MIS 12, 420- 470 ka BP). On seismic reflection profiles, the basal part of the Swarte Bank Fm. shows either chaotic reflections, or clinoforms. The upper part of the glaciogenic succession is attributed to the Egmond Ground Fm. of Holsteinian (interglacial) age. In high resolution seismic sections, it shows inclined/variable reflections which are usually of high energy. This unit is supposedly associated with a major postglacial transgression after the Elsterian glaciation.

Figure 1 Pleistocene tunnel valleys from the southern North Sea. Simple 'layer cake' internal architecture of tunnel valleys seen in cross section perpendicular to the valley axis may in fact result from complex clinoform patterns as shown in the section parallel to the valley axis. Seismic artefacts such as multiples are frequent when interpreting near-sea bottom stratigraphy.

In the southern North Sea, the glaciogenic sequence lies unconformably on the 'preglacial' sediments of Mesozoic-Palaeogene (mainly UK) to Pliocene (NL) ages, which are incised by tunnel valleys. The substratum of the glaciogenic sequence varies depending on the quantity of preglacial tectonic and halokinetic uplifts, and on the magnitude of the glacial incisions. There is a clear influence of the substratum on the regional geometry of the basal glaciogenic unconformity with deeper basins and tunnel valleys within the Tertiary basins (interfingered silts and sands), and higher plateaux and shallower tunnel valleys on the tectonic highs (principally cored by chalk). The orientation of the structural grain in the area is NW-SE (Fig. 1). Because the tunnel valleys mainly trend N-S, it is suggested that the tunnel valley orientation is predominantly driven by the ice sheets rather than by the substratum anisotropy (Moreau et al., 2012). The basal glaciogenic unconformity presents localised topographic thresholds often located at the termination of tunnel valleys where folds and thrust within the glaciogenic sequence are occasionally observed (Moreau et al. 2012). These features are interpreted therefore as offshore geomorphological expression of temporary stadial phases of ice sheet front, corresponding therefore to frontal moraine ridges in onshore location, such as those described onshore England and the Netherlands.

Figure 2 Time-depth map of the basal glaciogenic unconformity of the southern North Sea glaciogenic sequence showing the complex Quaternary tunnel valley system carved in the pre-glacial bedrock (Caenozoic and Mesozoic). Clear ridges and thresholds appear to characterise this surface suggesting possible temporary location of the ice sheet front (after Moreau et al., 2012).

A thorough examination of several existing descriptions of sedimentary records genetically related to tunnel valley environments, coupled with original study of selected outcrops and boreholes from the NW European region (England, Finland, Denmark, Netherlands) was carried out and comparisons made with a few localities in North America (Ontario Canada). The results of this study, summarised by van der Vegt et al. (2012), indicate that the sedimentary infilling of many tunnel valleys is associated with subglacial sedimentary processes, the amount and type of sediment load transported by the ice, and the interplay between ice movement, melting and grounding. In addition, decoupling and floating of the ice margin as a consequence of the formation of a proglacial water-body (marine or lacustrine) during ice withdrawal needs to be considered as does infilling of remaining topography during post glacial times. The topographic setting and isostatic rebound effects determine timing of inundation during postglacial sea-level rise. Geomorphic characteristics such as the steepness of the valley flanks and the depth of the negative relief left by the ice will also influence the final nature and architecture of the postglacial infill.

This study contributed to the ongoing, often animated, debate regarding the genetic processes of tunnel valleys, providing new evidence on the mechanisms responsible of initiating and controlling the incision of tunnel valleys (van der Vegt et al., 2012). In particular, a strong relationship between the contrast in permeability, porosity and cohesiveness between different layers of stratified bedrock (e.g. sand shale succession) on which the ice-sheet flows, and the morphology and depth of tunnel valley has been observed (see Janszen et al., 2012).

The detailed modelling exercise carried out using the large data set from the Hamburg area (Germany) has provided the opportunity to identify some common trends in the depositional infill with respect to specific morphological aspects of tunnel valleys (e.g. junction with tributary valleys, overdeepened areas etc). These can be used to define a number of guidelines on how to build static reservoir models of tunnel valleys, and a range of parameters to condition multiple subsurface realisations (Janszen et al., in prep). The use of 3D geo-modelling software has given the capability to assess various facies modelling techniques (e.g. object- vs. pixel-based modelling, use of trend maps, interpolation methods, etc.) and thus provide recommendations which will assist geoscientists in achieving realistic and effective subsurface static models.

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