3D Seismic Analysis of Pleistocene Tunnel Valleys in the Central North Sea

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This thesis is submitted to the University of London for the degree of Doctor of Philosophy (Ph. D) and the Diploma of Imperial College
Declaration

The work presented in this thesis is the candidates own. No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification in this or any other university or institute of learning.

[Signature]

Margaret A. Stewart
Abstract

Dense networks of glacial tunnel valleys were imaged at a regional scale beneath the central North Sea using commercial 3D seismic reflection datasets. Buried and seabed tunnel valleys were investigated with the aim of making progress in resolving their method of formation and relationship to the Pleistocene glaciations of the region.

The 3D seismic reflection datasets reveal that the buried tunnel valleys are characterised by cross-cutting relationships which provide the basis for the separation of generations of tunnel valleys. Up to eight cross-cutting generations of buried tunnel valleys were defined across an area of 100 x 100 km and provide conclusive proof that the tunnel valleys of the central North Sea are preserved as palimpsest landforms.

A single tunnel valley comprises the oldest generation of tunnel valleys identified in this work, and is found to predate the Bruhnes-Matuyama magnetic reversal at 0.78 Ma. This tunnel valley provides the first piece of direct evidence for a pre-MIS 19 glaciation in the central North Sea and associated with a cold period indicated in the marine isotope record at MIS 22. The seven younger buried generations of tunnel valleys correspond to seven peaks in the marine isotope record which indicate glacial episodes at MIS 18, 16, 12, 10, 8 and 6. This work finds that the tunnel valleys of the central North Sea record a much more complex glacial history for the North Sea than the current three-stage model and that significant ice sheets were present in the area much earlier in the Mid-Pleistocene than is currently accepted.

Analysis of the morphology and distribution of the buried tunnel valleys suggested their formation some distance from ice margins, possibly central to an ice mass controlled by multiple ice domes which provided hydrostatic head for tunnel valley initiation. Comparison between buried and seabed tunnel valleys reveal similarities in form, but differences in direction and distribution suggest that the configuration of the ice sheet at last glacial maximum (responsible for the formation of the seabed tunnel valleys) was significantly different to those responsible for the formation of the older, buried tunnel valleys.
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Chapter 1: Introduction and Rationale

1.1 Introduction and Aims

This thesis uses new evidence from 3D seismic reflection data to investigate extensive networks of buried tunnel valleys in the central North Sea. The results of the work presented here reveal a complex, cross-cutting character for many of the buried tunnel valleys over a much larger region than previously considered.

Although tunnel valleys have been recognised as glacial features both onshore and offshore since the early 20th century, their mode of formation continues to be debated. The relationship between tunnel valley incision and ice extent and dynamics also remains unclear, as do the Pleistocene ice limits and chronologies for the central North Sea region which is the focus of this work. This work presents the results of a comprehensive investigation of more than 180 buried and surface tunnel valleys in the central North Sea which makes significant progress with respect to these issues.

The aims of this work are summarised below:

1) To provide new insight into the character of more than 180 tunnel valleys imaged in the central North Sea using 3D seismic reflection datasets.

2) To use the results of investigations into the morphology and fill of the tunnel valleys to make progress in considering their method of formation.

3) To consider the character and location of the tunnel valleys with respect to the Pleistocene glaciations of the central North Sea in terms of extent, dynamics and chronology.

These aims are approached using the objectives defined below:

- Conduct reconnaissance mapping of tunnel valleys imaged within the 3D seismic datasets available in order to locate and prioritise areas of interest.
Investigate in detail the morphology of the tunnel valleys identified from reconnaissance mapping, and make systematic records of their geometry, depth and orientation.

Identify cross-cutting relationships between tunnel valleys (if any) and utilise the overlapping 3D seismic datasets to extrapolate these relationships across the study area.

Identify and characterise the acoustic properties of the tunnel valley infill with respect to location and geomorphology.

Use the results of the investigations above to relate the tunnel valleys to the stratigraphic succession of the central North Sea and in particular, attempt to divide further the regional seismostratigraphic Unit II identified by Graham (2007).

Identify any regularity in tunnel valley morphology and infill which can be related to the formation of the tunnel valley, particularly with respect to the debate regarding catastrophic versus steady state formation.

Identify any characteristics of tunnel valley form and fill which can be related to the extent and/or dynamics of the Pleistocene ice sheets in the region and consider possible ice configurations which would result in the tunnel valley observed.

1.2 Thesis Structure

Chapter 2 of this thesis provides a summary of the literature regarding tunnel valleys with an emphasis on the current debate regarding their formation. Comparison is also made to recent studies which are similar in nature to this investigation in terms of data and study area.
Chapter 3 outlines the regional background for this work with respect to the stratigraphy of the North Sea and its Pleistocene glacial history. The seismic stratigraphy constructed by Graham (2007) and adopted in this project is discussed in more detail.

The methods and datasets used within this work are the focus of Chapter 4, which outlines in detail how measurements of tunnel valley morphologies were obtained and analysed. Also discussed are the details of the commercial 3D seismic reflection datasets utilised in this work and associated data quality issues.

Chapter 5 presents the results of separating the buried tunnel valleys in the study area into a number of cross-cutting generations, at local and regional scales. The resulting framework is used as a basis for the remainder of the tunnel valley analysis carried out in this project.

The morphology of the buried tunnel valleys imaged within the study area are described in Chapter 6. Relationships between morphology, cross-cutting generations, location, and formation of the tunnel valleys are also considered within this chapter.

Chapter 7 presents the results of the investigation of tunnel valley infill carried out in this work, and also provides evidence to clarify the relationship of the buried tunnel valleys within the regional stratigraphic succession of the central North Sea.

Chapter 8 describes the seabed tunnel valleys imaged in the 3D seismic data utilised in the rest of this project, and from the high-resolution OLEX bathymetric dataset provided by the British Geological Survey. The morphology and orientation of the seabed tunnel valleys are discussed and compared to those of the buried tunnel valleys with respect to ice configuration for the last glacial maximum.

Chapter 9 synthesises the results of this work on the tunnel valleys of the central North Sea with respect to their formation and relationship with former ice sheets. A number of ice sheet configurations are presented to account for the formation and distribution of the tunnel valleys, and suggestions made for further work in the research area.
Chapter Two: Tunnel Valleys – Background

Tunnel valleys are linear incised landforms associated with ancient lowland continental glaciations. Individual and networks of tunnel valleys of Quaternary and older age are documented both on land and offshore, buried and at surface (Mooers 1989; O’Cofaigh 1996; Huuse and Lykke-Andersen 2000; Praeg 2003; Le Heron et al. 2004).

Tunnel valleys are recognised as important conduits for meltwater underneath continental ice-sheets and are interpreted as typical erosional landforms associated with such conditions. However, their formation and subsequent role in the glacial hydraulic regime is subject to debate (Stoker et al. 1985; Wingfield 1990; Mooers 1989; Brennand and Shaw 1993; O’Cofaigh 1996; Huuse and Lykke-Andersen 2000; Praeg 2003; Lonergan et al. 2006). The purpose of this chapter is to summarise the background literature regarding tunnel valley distribution, formation, morphology and fill characteristics.

Tunnel valleys obtained their name from the Danish ‘tunneldale’ describing their incised valley-type morphology as observed at surface (Madsen, 1921 c.f. Praeg, 1996), but are also referred to as tunnel channels, most commonly in the North American literature as outlined by Clayton et al. (1999) and Fisher et al. (2005, p. 2377). Specifically, the authors propose that ‘channel’ implies bank-full conditions during formation, whereas ‘valley’ suggests formation by smaller channel systems within a larger valley. Difficulties are encountered when naming is dependent on genetic origin, as there is as yet no agreement in the literature on nomenclature, or indeed formation methods for tunnel valleys. In this chapter I employ ‘tunnel valley’ as a descriptive term and do not associate its use with any particular mode of formation.

2.1 Location of Referenced Works

Features recognised as tunnel valleys are distributed worldwide in formerly glaciated lowlands. Tunnel valleys and tunnel valley systems are recognised in north-west Europe, North America, northern Africa, the Middle East and western Australia (Mooers 1989; O’Cofaigh 1996; Eyles and de Broekert 2001; Hirst et al., 2002).
In northwest Europe, tunnel valleys are associated with the Late Quaternary glaciations of the Pleistocene epoch, spanning ca. 1.8 Ma BP to present (Hambrey, 1994). O'Cofaigh (1996) and Huuse and Lykke-Andersen (2000) usefully summarise the distribution and estimated age for a number of tunnel valley studies in the region (Figure 2.1). A recent special issue of *Journal of Applied Geophysics* (v.53, 2003) also contains a number of papers on tunnel valleys and their application to the exploitation of groundwater resources in lowland Europe. Tunnel valley studies referenced in this work are described on mainland Europe in Poland (Pasierbski, 1979; Dobracki and Krzyszkowski, 1997; Marks, 2005), northern Germany (Grube, 1983; Bruns, 1989; Ehlers and Linke, 1989; Piotrowski, 1994, 1997; van Dijke and Veldkamp, 1996; Piotrowski et al., 1999; Piotrowski and Tulaczyk, 1999), Denmark (Huuse and Lykke-Andersen, 2000; Sandersen and Jørgensen et al., 2003; Jørgensen and Sandersen, 2006), southern Sweden (Lidmar-Bergström, 1991) and the northern Netherlands (van Dijke and Veldkamp, 1996; Kluiving, 2003). Onshore UK tunnel valleys in eastern England are described by Woodland (1970), Lake et al. (1977), Cox (1985) and Cornwell and Carruthers (1986).

A number of tunnel valley studies have been undertaken in the southern North Sea, focusing particularly on the Danish sector (Huuse and Lykke Andersen, 2000; Kristensen et al., 2007). Praeg (1996, 1997, 2003) presents a particularly relevant study of tunnel valleys in the southern UK sector of the North Sea using 3D seismic datasets. Balson and Jeffery (1991) also identify tunnel valleys in the UK sector south of 55°N. Tunnel valley systems have also been studied offshore Germany (Gabriel et al., 2003) and southern Sweden (Lidmar-Bergström et al., 1991), as well as in the English Channel (Smith, 1985) and the Irish Sea (Whittington, 1977; Eyles and McCabe, 1989; Wingfield, 1989). Recent work in northern Russia and the Barents Sea (Siegert et al., 1999; Svendsen et al., 2004) also describes features resembling tunnel valleys.

(2008) use bathymetric data to identify seabed tunnel valleys in the central and northern North Sea.

Tunnel valley distribution in North America is related to the extent of the Laurentide ice sheet, which was centred on eastern and central Canada during the Pleistocene and extended southwards into the northern United States. Figure 2.2 shows the location of many of the studies cited in this work. Tunnel valleys are identified on land in Ontario (Brennand and Shaw, 1994; Barnett et al., 1998; Boyce and Eyles, 2000; Russell et al., 2003), Alberta (Evans et al., 1999; Beaney and Hicks, 2000; Rains et al., 2002), Saskatchewan (Christiansen, 1987), Minnesota (Wright, 1973; Mooers, 1989; Patterson, 1997), Michigan (Fisher and Taylor 2002; Sjogren et al., 2002; Fisher et al., 2003, 2005), Wisconsin (Clayton et al., 1991, 2001) and New York (Pair, 1997). Smaller tunnel valley systems are also associated with the Cordilleran ice sheet in Washington, and northwest Canada (Booth and Hallet, 1993; Brennand and Sharpe, 1993). Offshore systems are described in Hudson Bay and the Scotian shelf off northeast Canada (Boyd et al., 1988; Loncarevic et al., 1992), and on the New Jersey shelf off the northeast coast of the United States (Davies and Austin, 1997).

Ancient tunnel valleys in North Africa and Arabia (Fig 2.3) have been described by Vaslet (1990), Abed et al. (1993), Powell et al. (1994), Ghienne and Deynoux (1998), Janjou et al. (1998), Senalp and Al-Laboun (2000), Senalp and Al-Duaiji (2001), Hirst et al. (2002), Smart (2002), Le Heron et al. (2004, 2006) and El-ghali (2005) and are associated with the Late Ordovician glaciation of Gondwanaland, where the northern margin of the Ashgillian ice sheet is thought to have been situated partly in Algeria (Sutcliffe et al., 2000; Senalp and Al-Laboun, 2000; Hirst et al., 2002; Le Heron et al., 2004, 2006). A tunnel valley system has also been identified in Western Australia and attributed to the Early Permian glaciations of Gondwana (Eyles and de Broekert, 2001).

2.2 Theories of Tunnel Valley Formation

The vast majority of evidence now points to a subglacial meltwater origin for tunnel valleys, which is generally accepted by most workers in the field (O'Cofaigh, 1996; Benn and Evans, 1998; Huuse and Lykke-Andersen, 2000). Tunnel valleys provide geomorphological proof of channelisation beneath former continental ice sheets at least an order of magnitude larger than other landforms indicative of subglacial meltwater
such as Nye channels and eskers (Sugden and John, 1976; Benn and Evans, 1998). However, there is little agreement regarding the particular hydraulic regime and processes responsible for the formation of the tunnel valleys. Currently, the main hypotheses concerning tunnel valley formation can be separated into steady-state versus catastrophic models, although some workers are now taking a polygenetic approach where a number of mechanisms are responsible for tunnel valley formation. In general terms, the steady-state argument advocates the diachronous formation of tunnel valleys beneath retreating ice sheets whereby pressurised meltwater excavates, modifies, and provides partial fill for tunnel valleys at the ice margin. The opposing hypothesis suggests instead rapid tunnel valley erosion by episodic subglacial meltwater outburst events.

Part of the problem may be the variety of features in diverse geographical locations described as tunnel valleys. As Huuse and Lykke-Andersen (2000, p.1233) summarise, “much of the controversy appears to originate from the search for a single commonplace mechanism to explain features ranging from m-scale to km-scale in a wide variety of settings”. The history of the tunnel valley concept and its application to landforms in Europe and North America up until 1990 reflect this issue; many of the studies are considered individually and were conducted with only one formation theory in mind.

2.2.1 History of the Tunnel Valley Concept in Europe

Much of the earliest work on tunnel valleys was conducted in northern Germany and Denmark in the late 19th and early 20th century, and it provides a relevant context for the current debate regarding steady-state versus catastrophic origin for tunnel valleys. Channel features (Rinnen from the German for channel), sometimes occupied by chains of elongate lakes (Rinnenseen), were seen to cut into the otherwise subdued topography of northern Germany and Denmark, and were at first interpreted as tectonic in nature (Berendt, 1863, c.f. Pasierbski, 1979).

Following the introduction and spread of glacial theory in northwest Europe, authors such as Berendt (1879, c.f. Pasierbski, 1979) reverted from their previous tectonic stance and advocated erosion of tunnel valleys by glacial meltwater. Jentzsch (1884, in Pasierbski, 1979 and Praeg, 1996) was the first author to suggest a subglacial origin for the channels, and in fact proposed their formation as a result of subglacial streams.
Ussing (1903, c.f. Pasierbski, 1979 and Praeg, 1996) and then Werth (1907, c.f. Pasierbski, 1979 and Praeg, 1996) of the Danish Geological Survey (DGS), took the concept further, particularly in emphasising the role of meltwater under pressure as necessary for the reverse gradients observed within the channels, and in relating the channels to outwash plains and end moraines. Channels were interpreted as forming transverse to retreating ice margins, thus accounting for their regular distribution, previously linked to structural or tectonic influences.

Madsen (1921, c.f. Praeg, 1996), was the first to introduce the term *tunneldahle*, which became widely accepted in its original Danish, and later as ‘tunnel valley’ in English, first championed by Woodland (1970). Wolff (1907, 1909, c.f. Ehlers and Linke, 1989) found evidence for significant buried channel networks in the Hamburg and Bremen areas of northern Germany and concluded their origin was due to pre-glacial fluvial processes. Woldsted (1923, 1926, 1954 in Pasierbski, 1979) was initially in agreement with Ussing and Werth regarding a subglacial origin for surface tunnel valleys, but later cited erosion by direct glacial contact as more influential – a decision which influenced many of his contemporaries. During the 1970’s, many Danish authors (e.g. Hansen, 1971) rejected the arguments of Ussing, and argued that tunnel valleys were the result of direct glacial erosion, glacial modification of pre-existing fluvial valleys, or of other processes including periglacial slumping and local neotectonics (see summary in Krüger, 1983).

Polish authors, however, tended to side with subglacial erosion by meltwater, as summarised by Pasierbski in his 1979 review and by Praeg (1996). Authors such as Galon (1965) and Kozarski (1966) re-examined the morphological characteristics of the tunnel valleys and their association with depositional landforms such as outwash fans and eskers across the Baltic lowlands, widely recognised as indicative of the last deglacial landscape. Their conclusion was that tunnel valleys were the result of pressurised drainage beneath continental ice sheets; a return to the original views of Ussing and Werth, and one now generally accepted across Europe (O’Cofaigh, 1996; Praeg, 1996; Huse and Lykke-Andersen, 2000).

Onshore UK, channel features sometimes described as tunnel valleys are generally restricted to the southeast (East Anglia, Suffolk, Norfolk and Essex) and are usually
buried with little surface expression. Large thicknesses of Quaternary ‘drift’ (unspecified glacial sediment) infilling the channels have been noted since the late 19th Century, usually as a result of boreholes drilled in connection with industry, water and sewage works. Phear (1856) identified the unusual thicknesses of ‘Boulder Clay’ in the Gipping Valley of Suffolk as a result of tectonic fracture and uplift.

It was Boswell (1913) who first made a direct comparison between the buried channels in East Anglia and the tunnel valleys of Denmark and northern Germany, although the author tended towards pre-glacial excavation and subsequent widening by direct ice contact as responsible for their dimension, rather than a solely subglacial meltwater origin. However, in a discussion regarding future work on the extent of the valleys, the author mentions “the possibility that the hollows ended abruptly, as would be expected by sub-glacial water-streams” (Boswell, 1913, p. 620). His figure showing a longitudinal section down the Brett valley is very similar to work produced on tunnel valleys today, with deep hollows containing fill and no constant downstream deepening (Figure 2.4).

Outwith East Anglia, a large, well-developed anastomosing system of channels and eskers in Lanarkshire was documented by Sissons in 1961, notable for its scale. The author mentions a “complex anastomosing system” and an “up-and-down long profile” which may have required “a subglacial stream to have eroded while climbing uphill through a vertical distance of 250 ft” (Sissons, 1961, p. 179). Well-preserved bedding in a steep sided esker associated with the system was also used to provide evidence for a subglacial origin beneath a stagnant wasting ice sheet during the last glaciation.

Woodland’s 1970 work summarised the history of previous work in East Anglian tunnel valleys, and presented a comprehensive survey of the 400 boreholes then available which provided evidence for unusual thicknesses of drift, comprised of locally derived sands and muds, within the channels. His conclusions are in general agreement with Boswell (1913), namely that the “tunnel valleys of Denmark and the Rinnen of north Germany are essentially the same as the buried channels of East Anglia” (Woodland 1970, p. 557) and that the tunnel valleys were cut at the same time as large till sheets were deposited, with the sands and muds deposited by subglacial streams.
Of interest are his notes on the morphological difference between the East Anglian and Danish tunnel valleys, with the former being generally thinner and narrower (~500 m wide and > 100 m deep) than the latter (~2 km wide and 20 – 100 m deep) for which he gives three reasons: Firstly, the chalk substrate into which the East Anglian tunnel valleys are cut is significantly less susceptible to lateral erosion than the clastic sediments of the Danish and German examples; valley side walls in these examples would be likely to collapse, preventing the formation of deep channels. Secondly, the fissured nature and high permeability of chalk in the area allows unhindered drainage, further enhancing the possibility of high, stable valley walls. Finally, the East Anglian ice and meltwater was relatively ‘dirty’ (containing large amounts of supraglacial debris and water-borne gravel) which encouraged downwards excavation in comparison to the ‘clean’ glaciation of Denmark and Germany. This latter point in particular may now be debated with reference to current attitudes to subglacial hydrological processes, but Woodland’s argument is otherwise well-made, citing some examples of tunnel valley adjustment to narrower, deeper forms when incised into the narrow outcrops of chalk in eastern Denmark (Sorgenfrei and Berthelsen, 1954, c.f. Woodland, 1970, p. 556).

D'Olier (1975) described tunnel valleys in the eastern part of the London Basin, trending NNE-SSW in the Thames estuary, near to the East Anglian examples. D'Olier (1975, p. 275) also suggested that the geomorphological character of the features (i.e. low sinuosities, undulating long profiles, abrupt start and end points) lead to the conclusion that the channels were “tunnel valleys formed by subglacial meltwater channels running under ice near its margins with a considerable hydrostatic head”.

Cox (1985), however, refuted the above conclusions in his detailed study of three of the same valley systems as Woodland (1970) in Norfolk using purposely drilled boreholes. Instead, he argued that pre-glacial drainage at a lower sea level than present, followed by local over-deepening as a result of direct glacial erosion was responsible for the channels and their observed undulating longitudinal profiles. He also suggested that for some channel systems, periglacial solifluction widened streams in cold periods and provided an extra source of sediment fill. Cornwell and Carruthers (1986) used a number of geophysical methods including gravity surveys, resistivity soundings, conductivity mapping and seismic refraction surveys to re-map the fill of the channels investigated by Woodland (1970) and Cox (1985) in the Ixworth area of Suffolk. Their
findings suggested that much of the 'drift' material surveyed by Woodland was in fact glacial till, and mapped its distribution to confirm Woodland's report that the channels were tunnel valleys formed subglacially. Cornwell and Carruthers (1986) and Ehlers and Gibbard (1991) also concluded that the East Anglian tunnel valleys were older than had been previously interpreted and dated from the Anglian glaciation.

Research on seabed tunnel valleys in the UK sector of the North Sea spans more than 170 years and reflects the influence of European theories. The Silver Pits offshore of East Anglia (Figure 2.1) were no doubt well-known by local fishermen for some time, but were first approached geologically by De la Beche in his 1834 book "Researches in Theoretical Geology". It is apparent from this work that the Royal Navy were aware of the NW-SE trending "trough-like cavities" (de la Beche, 1834, p. 109), in the otherwise "great tract of plain" (p. 191) comprising the submerged North Sea area. De la Beche suggested that the deeps were a result of cracking from upward bending of the strata beneath as he could see no evidence for similar patterns of fluvial erosion either on the nearby coast or onshore.

Following the acceptance of the glacial theory in Europe and the UK, Gregory's 1931 report (Gregory 1931) on soundings of the Devil's Hole channels (Fig 2.1) concurred with prior descriptions of their position on Admiralty maps, and concluded that the features were remnants of a pre-glacial fluvial system stretching north from the present mouth of the Rhine. Lewis (1935) agreed with this theory and attributed further 'deeps' found nearby to the lateral migration of such a fluvial system.

Robinson (1952) was the first author in the English literature to recognise a direct glacial influence for the offshore 'deeps' — noting that North Sea ice would divert fluvial drainage systems on the mainland, as well as suggesting that the Devil's Hole channels may have been partially excavated by stagnant ice. Valentin (1957 c.f. Praeg, 1996) went further and suggested the incised channels offshore East Anglia (including the Silver Pits) were formed beneath a lobe of the British Ice Sheet during its final stages of retreat. Flinn (1967) and Robinson (1968) also favoured a subglacial stream hypothesis for the Devil's Hole and Silver Pit channels.
Donovan (1965) used limited 2D seismic data to re-interpret the Silver Pit channels as tidal scour hollows formed post-glaciation, but later reconsidered their genesis as at least partly subglacial (Donovan 1973). Dingle (1971) found extensive buried tunnel valley systems using single channel 2D seismic reflection profiling west of Dogger Bank, and suggested their formation and fill by marginal subglacial streams. Jansen (1976) continued this survey to the north, but preferred a proglacial origin for the buried channels.

British Geological Survey (BGS) seismic survey programmes and commercial exploration in the North Sea basin during the 1970's continued to provide evidence for extensive Quaternary buried tunnel valleys systems at a number of stratigraphic levels. Thomson and Eden's 1977 study was limited by >10 km spacing between profiles in the seismic survey, restricting their mapping to cross-profile representation of the channels, but Holmes (1977) was able to describe branching patterns in planform for a small, shallow sets of buried valleys in the Fladen area. In general, these early works were constrained by the aliasing effects of 2D profiling where survey spacing was not sufficiently dense to reconstruct the planform arrangement of the buried tunnel valleys (Brown 1999). This problem can be tackled by using 3D seismic reflection datasets as in this work, and is discussed further in Chapter 4.

Stoker et al. (1985) provided some control on the age of the buried tunnel valleys in the central North Sea by finding the Bruhnes-Matuyama magnetic reversal (ca. 0.75 Ma BP) in the Aberdeen Ground Formation, into which the buried tunnel valleys incise. The successive layers of tunnel valleys were then more confidently associated with the three accepted glaciations of the Pleistocene (for further discussion see Chapter 3). However, Stoker and Bent (1985) cited an apparent lack of evidence for glacial conditions in the central and northern North Sea during the last glaciation (Weichselian), implying that a subglacial origin for some of the buried tunnel valleys was untenable as they were beyond the borders of till sheets. Long and Stoker's 1986 summary of buried and open tunnel valleys in the central North Sea therefore proposed that the tunnel valleys were a result of proglacial fluvial erosion during glacial lowstand, followed by periglacial modification. Cameron et al.'s 1987 study also suggested a similar, non-subglacial origin for the buried tunnel valleys in the northern North Sea.
Further controversy was ignited by the work of Wingfield (1990), who suggested that North Sea and Irish Sea tunnel valleys at seabed were formed by headward erosion of ice sheets, initiated by catastrophic jökulhlaups behind a frozen toe at ice margin; necessitating Weichselian ice cover in the region. Wingfield’s (1990) work was disputed by Jeffrey (1991) as contrary to work by Balson and Jeffrey (1991) which used the analysis of ten boreholes and seventy shallow cores in the area to show a lack of evidence for high velocity fluvial discharges topped by periglacial deposits as would be expected from Wingfield’s hypothesis. Instead, Jeffrey (1991) and Balson and Jeffrey (1991) found the borehole sediments to comprise stiff diamicton overlain by laminated sandy muds, and interpreted the seabed tunnel valleys as subglacial features cut by pressurised meltwater. In their model, summer melting initiated the excavation of shallow channels by sediment deformation and creep as in Boulton and Hindmarsh (1987). Winter refreezing closed the channels, but the next cycle of summer melting reused previous drainage pathways, eventually resulting in the deep incisions observed.

Ehlers and Wingfield (1991) also supported the notion of tunnel valley incision by subglacial meltwater, inferring Weichselian ice sheets in the region and arguing that a lack of till was not necessarily indicative of non-glaciation as till in ice marginal areas onshore was often found to be thin and discontinuous.

2.2.2 Development of North American Theory

The tunnel valley concepts developed in Europe for more than a hundred years were not applied widely to North America until Flint’s 1947 textbook compared ‘trench systems’ in western Canada to the Rinnen in northern Germany. Thwaites (1943) briefly mentions incised “kettle-chains” as significant landforms in his mapping of glacial deposits in eastern Wisconsin, but does not elaborate much further as to their formation. Work by Gravenor and Kupsch (1959) in western Canada also described the ‘stream-trench’ systems of Flint, but instead proposed formation in ice-walled channels which formed beneath the disintegrating Laurentide ice sheet.

In 1973, Wright published a detailed study of incised linear ‘trenches’ in Minnesota associated with the Superior Lobe of the Laurentide ice sheet, and specifically related them to the tunnel valleys of Denmark. He found that many of the trenches contained large eskers, and that the system displayed discordant palaeoflow direction when
compared with the southerly drainage of the current stream network. Wright (1973, p.256) went on to state that “the tunnel valley courses were determined not by the slope of the substratum but by something else, specifically the slope of the inferred ice surface”, implying a subglacial origin for the tunnel valleys and associated eskers controlled by the hydrostatic pressure gradient of the Superior Lobe. The author suggested that meltwater from the interior (warm-based) part of the lobe accumulated for thousands of years, but was prevented by drainage at the glacier toe due to frozen bed conditions beneath the shallower ice. Eventually, the pressure and volume of meltwater caused a catastrophic breach of the frozen toe; very high velocity flows of pressurised meltwater eroded the tunnel valleys “simultaneously throughout their length” (Wright, 1973, p.265). Eskers were formed during waning flow after initial excavation, when hydrostatic head lowered sufficiently to favour deposition.

Although the frozen toe theory above is described as a catastrophic approach, Wright does discuss the possibility that the tunnel valleys may have eroded headwards beneath the ice, and non-synchronously, due to the presence of occasional cross-cutting relationships between individual branches of tunnel valleys. However, he argued that meltwater discharge from basal steady-state melting would insufficient to cut the tunnel valleys and supplemental supraglacial sources would also fail to provide a sufficient volume of meltwater. He does concede that the eskers may have formed progressively headward during deglaciation as the lobe thinned.

Clayton et al., in their 1985 review of surging and ice streaming of the Laurentide ice sheet, mention tunnel valleys in the Minnesota, Wisconsin and Indiana areas as important subglacial meltwater conduits. The authors make an important connection between substrate and landform formation, noting that tunnel valleys are found mainly in areas of non-permeable clastic sediment. In these conditions, they suggest subglacial pore pressure became high enough in the course of basal meltwater flow for the ice-sheet to decouple from the substrate, enhancing subglacial flow and channelisation.

Christiansen (1987) studied an isolated valley and esker system in south west Saskatchewan and compared its morphology directly to the Danish tunnel valleys. He used the presence of fining-up sequences in both the valley and the esker to suggest the features formed over time, with the tunnel valley developing by headward erosion
transverse to the ice margin. At some point, he proposes that the roof of the tunnel collapsed near to the ice margin, creating an ice-walled channel in which the esker was deposited. He uses the scarcity of other esker features nearby to propose that the ice margin remained stationary during this process, stating that if “the ice margin had retreated during the formation of the valley, other eskers like the Glidden esker should be found” (Christiansen, 1987, p. 172).

Mooers (1989) re-examined some of the tunnel valleys of the Superior Lobe in Minnesota, emphasising the need for supraglacial (surficial) melting as an important source of meltwater for the formation of tunnel valleys. He proposed that seasonal melting in a relatively mild summer produced the significant amount of meltwater required to erode tunnel valleys, basal meltwater alone being insufficient. As the ice margin retreated, the tunnel valleys extended headwards and merged, creating the (minimal) anastomosing pattern observed. Eskers present within the tunnel valleys were deposited at a latter stage by sediment-rich meltwater flowing under a reduced hydrostatic pressure (as the ice sheet thinned), or possibly synchronously, as “tunnel valleys may have been forming some distance up-glacier, and the contribution of sediment from the ice surface near the margin may have been enough to change the subglacial streams to a depositional mode” (Mooers, 1989, p. 33). Mooers’ theory does not require the build up of substantial reservoirs of meltwater to contribute to a catastrophic flood origin for the tunnel valleys but instead takes a more steady-state approach, although his calculations do not allow for sufficient basal meltwater to account for the scale of tunnel valleys observed in a steady-state model with deformable substrate (i.e. that of Boulton and Hindmarsh, 1987).

Attig et al. (1989) surmised that the Laurentide ice sheet in the western Great Lakes (the Des Moines lobe in northern Minnesota and the Superior Lobe in Wisconsin) reached its maximum between 18 ka and 15 ka B.P, finally retreating from northern Wisconsin ca. 9900 B.P. Although marked by intervals of advance and retreat, maximum ice extent persisted in the regions of tunnel valley formation discussed by Mooers (1989) and Wright (1973) for up to 5000 years. Combined with the work of Clayton et al. (1985) on the importance of elastic substrate in the formation of tunnel valleys, it appeared that there was a strong argument against the necessity of catastrophic flooding as a source of meltwater for tunnel valleys in this region. As shown in Figure 2.5, Attig et al. (1989)
supported a frozen toe theory for tunnel valley formation, with permafrost at the ice margin acting as a barrier to meltwater from the warm-based interior of the ice sheet, leading to the catastrophic incision of tunnel valleys at the margin.

However, in the early 1990s the influential work of John Shaw on subglacial drainage resulted in a number of studies which relied heavily on catastrophic flooding as the main formation method for drumlin fields and other associated the glacial landforms such as Rogen moraines, hummocky moraines and tunnel valleys in North America and principally Canada (Shaw, 1983, 1993, 2002; Shaw et al., 1993; Brennand and Sharpe 1993; Brennand and Shaw, 1994). Shaw’s work arose from the need to describe large drumlin fields, which he described as erosional features and posited as proof of widespread subglacial sheet flooding during the Laurentide glaciation. The main proponents of catastrophic flooding theories suggest that turbulent sheet-flooding beneath an ice sheet (initiated by the release of large volumes of meltwater) was inherently unstable and would eventually channelise, leading to the formation of erosional tunnel valleys possibly some distance away from ice margin. The theory differs from that proposed by Wright (1973) as it does not require a ‘frozen’ ice margin, and, in fact, is not related to ice marginal retreat.

Much of the controversy associated with these studies relates to the debate regarding catastrophic flooding and drumlin formation, a very large topic which was approached critically by Maizels and Russell (1990), and summarised by Benn and Evans (1998, p. 431 - 437). Based on form analogy with scabland features, and sedimentological analysis of the drumlins themselves, Shaw’s hypothesis is that drumlins were formed during ‘mega-floods’ by infilling of scours cut upwards into the ice, or by the excavation of sediment between pre-existing bedforms if the drumlins are sediment-cored. In general, the aspects relevant to tunnel valley formation are confined to whether drumlins are erosional or depositional features, and where they form in relationship to the ice margin; the ‘mega-flood’ hypothesis is often applied indiscriminately to tunnel valleys in areas where it has been used to explain formation of drumlin fields.
2.2.3 Current Arguments: Steady State vs. Catastrophic

From the history of the tunnel valley concept in Europe and its development in North America come the main threads of the current arguments regarding tunnel valley formation. The effects of substrate, position with respect to the ice margin, and perhaps most importantly, deformable bed and steady-state theory versus mega-flood origins for the features dominate the current debate. Marshall (2005) provides a good introduction to current work on subglacial hydrology.

2.2.3.1 Steady-State Models

Those workers in favour of a more steady state system for tunnel valley formation focus mainly on subglacial channel formation with respect to the pressure systems, hydrological regime, ice characteristics and sediment or bedrock properties beneath the ice sheets associated with the tunnel valleys. Many of the associated theories are reliant on the presence of a deformable bed beneath the ice sheet, an idea originally proposed by Boulton and Hindmarsh (1987) which is gaining widespread acceptance (Benn and Evans, 1998; Huuse and Lykke-Andersen, 2000; Boulton et al., 2001; Flowers and Clarke, 2002; Dowdeswell et al., 2002; Evans and Twigg, 2002; Van der Meer et al., 2003; Ehlers and Gibbard, 2004; Evans et al., 2005; Boulton, 2006; Evans, 2006)

Originally, Boulton and Hindmarsh (1987) argued that tunnel valleys were a type of Röthlisberger channel (R-channel), that is, one cut up into ice rather than down into sediment (their model does not apply to bedrock areas). They propose that the initiation of such channels begins when porewater pressure in subglacial (deformable) sediment is high, causing liquefaction and flow outwards towards the proglacial zone. The resulting depression in the substrate is kept open by meltwater flow and evolves by headward erosion away from the region of high porewater pressure (Figure 2.6a). Sediment creep and deformation will act to close the channel, and so must be countered by high meltwater volumes, the source of which the authors assume to be basal meltwater from the temperate internal regions of an ice sheet.

Working within the framework of deformable bed sediments, Walder and Fowler, (1994) proposed a theoretical model predicting steady-state channel development by sediment creep in saturated subglacial sediment, although their model was confined to cm-scale 'canal' features. Continuing in this vein, Van Dijke and Veldkamp (1996)
suggested that large channels were initiated when significant influxes of meltwater from surficial melting prevented the underlying aquifer transporting water by internal flow. As a result, the hydrological system of the ice becomes unstable, and channels cut down directly into the bed in order to cope with the flux. These N-type channels (Nye, 1976) are eventually sufficient to return the system to a stable state, where Darcian flow through the underlying aquifer is resumed. The changes in meltwater input rely on supraglacial melting variability related to temperature change, with water being transported to the bed via crevasses. Van Dijke and Veldkamp (1996) suggested that temperature variation during rapid and variable deglaciation could produce the systems of tunnel valleys seen in northwest Europe whereby the differences in base profiles within the tunnel systems indicate changes between steady state aquifer and unstable channel drainage.

A second variation on the steady-state model for tunnel valley formation has been proposed by Praeg (1996, 1997, 2003) and is similar to that of Mooers (1989) as discussed above. In this model, tunnel valleys form over time by headward erosion from ice margin during retreat, in a mode very similar to that of eskers. Proximity to ice margin and the large volumes of surficial meltwater, as outlined by Van Dijke and Veldkamp (1996), are key. Praeg advocates simultaneous filling during excavation, with glacio-fluvial erosion upstream backfilling towards the outer tens of kilometres of the northerly retreating Elsterian ice sheet. Evidence is provided by the large scale axially downlaping clinoforms (2 – 20 km in length and up to 400m in height) imaged in seismic reflection data and combined with lithological information from boreholes. In Praeg’s model, the observed size of the tunnel valleys does not reflect bankfull conditions at the time of formation, instead, a smaller system of subglacial streams “feed subaqueous marginal fans within the larger tunnel-valley basins”. Surficial melting during retreat is the dominant source of meltwater, and there is no requirement for catastrophic outbursts. He concludes that in his study area, “the tunnel-valleys record the diachronous coupling of substrate and glacier hydrology beneath the receding, melting ice sheet margin” (Praeg, 1996, p.iii).

Pair (1997) also proposed a relatively steady-state subglacial meltwater model for the formation of tunnel valleys in northern New York, based on the incision of the valleys into a hard limestone substrate which controlled their original form. However, the
author also found evidence for striations within the tunnel valleys, indicating that many of the valleys were ice-filled and so a polygenetic origin must be concluded.

In 2000 Huuse and Lykke-Andersen published their study of tunnel valleys in the Danish North Sea, based on high resolution 2D seismic profiles, and concluded that their formation was related to multiple cycles of down-cutting eventually resulting in large incised tunnel valleys. They did not conclude definitively whether meltwater was supplied catastrophically or more constantly but tended towards the latter due to the significant length of the valleys and the unlikelihood that catastrophic flooding alone would be sufficient to excavate the tunnel valleys along their entire length. The authors were keen to stress the variability of surficial melting, much as the work of VanDijke and Veldkamp (1996) and Praeg (1996, 2003), where cyclic variations in melting would encourage subglacial channel cutting during high flow periods, and closure by creep during low discharge. Over the period of a glaciation (thousands of years), the authors argue that “such an arrangement would probably mimic a ‘steady-state’ down-cutting of a sub-glacial valley” (Huuse and Lykke-Andersen, 2000, p. 1249). The authors also considered that some of the more shallow valleys may have been modified by direct ice contact, and generally advocate a polygenetic model of formation with steady-state, catastrophic and ice contact processes all playing a part in tunnel valley formation.

Based on analysis of fill and morphology Huuse and Lykke-Andersen (2000) also suggested that the complex system of anastomosing tunnel valleys may have resulted from multiple episodes of ice advance and retreat. Tunnel valleys would eventually be filled with dead ice and sediment, so that when subsequent advances initiated fresh down-cutting, the resulting tunnel valley patterning could vary significantly, leading to multiple generations of cross-cutting valleys with overdeepened reaches and complex planform geometries. However, the ~20 km line spacing of the survey caused problems with spatial aliasing which left the authors unable to distinguish whether individual valleys were truly anastomosing or displayed cross-cutting relationships.

In 2003 the Journal of Applied Geophysics published a special issue on geophysical investigations of buried tunnel valleys in north-west Europe which included a number of works important to this work and to steady-state formation theories. Praeg’s (2003) paper again emphasised his findings that tunnel valleys formed by headward erosion
behind a retreating ice margin, while Kluiving et al.'s (2003) correlation of onshore and offshore tunnel valleys in the Netherlands, based on 2D seismic profiling and targeted boreholes, also favoured a steady-state formation method; their work found millimetre-scale lithofacies variability within tunnel valley fill that excluded a catastrophic origin and proposed a complex history of tunnel valley incision with multiple episodes of ice advance and retreat. In the same volume, Sandersen and Jørgensen (2003) also conclude that the Danish tunnel valleys were likely incised and reworked by multiple episodes of ice advance and retreat, and may have been re-used during a number of glacial cycles.

Jørgensen and Sandersen's 2006 work on buried and open tunnel valleys in Denmark, based on TEM data, some shallow 2D seismic profiles and boreholes, considered subglacial meltwater flow to be the main agent of erosion, with perhaps some modification by ice. They found evidence for multiple generations of tunnel valleys forming complex cross-cutting networks, and for the re-use of pre-existing tunnel valleys during subsequent glaciations. The authors advocated erosion by outbursts of stored meltwater, but in smaller channels within the tunnel valleys, rather than as the bankfull phenomena described by Shaw (1994) and others. This method of erosion, "in small channels situated on the valley floors" has more in common with the theories of Praeg (1996, 2003) and Huuse and Lykke-Andersen (2000) and is considered to be closer to a steady-state argument than catastrophist, especially if considering meltwater influx to be variable depending on surficial conditions as in VanDijke and Veldkamp (1996). Furthermore, the authors do not rule out the importance of steady-state "meltwater in laterally migrating conduits" as contributory to the erosion of tunnel valleys (Jørgensen and Sandersen, 2006, p. 1359).

Lonergan et al. (2006) observed four generations of cross-cutting tunnel valleys in the central North Sea using 3D seismic data. They concluded a relatively steady-state formation model for the tunnel valleys with incision occurring over multiple episodes of ice advance and retreat. Fill analysis revealed a middle unit correlated to the lower, unstructured unit of Cameron et al. (1987) and Huuse and Lykke-Andersen (2000), and the clinoform surfaces of Praeg (1996, 2003), which the authors characterised as wedge shaped packages of gently dipping reflectors. The unit, up to 40 m thick, is often found at tributary junctions and may extend axially for up to 3 km. In places, individual wedges can be seen to downlap the underlying basal topography, implying deposition.
under pressure. The authors use this as evidence to suggest that pressurised meltwater not only carved the tunnel valleys but also deposited part of the tunnel valley fill.

Lonergan et al. (2006) also emphasised the importance of supraglacial meltwater released during retreat and thinning and so promote an episodic but not catastrophic mode of subglacial meltwater discharge and therefore tunnel valley incision and reuse. Similarly, Kristensen et al. (2007) utilised 3D seismic reflection datasets to study cross-cutting tunnel valleys in the eastern North Sea. Their work finds between five and seven generations of cross-cutting tunnel valleys, each related to an ice advance/retreat cycle and a two-unit fill comprising a clinoform seismic unit overlain by a layered seismic unit. The basal clinoform unit is compared to that observed by Praeg (1996, 2003) and the authors suggest the unit may have formed in a similar manner. Detailed geomorphological measurements made by the authors also allowed for calculations to be made which confirmed glaciologically that meltwater in the tunnel valleys was able to flow uphill.

In summary, recent work which considers the steady-state formation method for tunnel valleys is concerned with the effect of widespread deformable beds, the input of water via surficial melting, similarity to esker formation processes, multiple episodes of tunnel valley incision and the possibility that direct glacier erosion may be influential in the resulting landforms. Authors such as Huuse and Lykke-Andersen (2000) stress that tunnel valleys may in fact display polygenetic origins, and recent work on high-resolution 3D seismic data work by Lonergan et al. (2006), Jorgensen and Sandersen (2006) and Kristensen et al., (2007) emphasises the importance of possible reworking and re-use of tunnel valleys between successive glaciations and advances.

2.2.3.2 Catastrophic Models

Current theories for catastrophic tunnel valley formation can in most cases be split into two broad variations: those in which tunnel valleys form when meltwater is released catastrophically from behind a 'frozen' ice margin, and those in which tunnels form in response to hydrologically unstable catastrophic subglacial sheet-floods some distance from the ice margin (see summary in O'Cofaigh, 1996). In both cases, it is generally argued that valley systems are cut simultaneously along their entire length during
bankfull conditions; the distinction used by Clayton et al. (1999) as in Figure 2.6b, to apply the term ‘tunnel channel’ to features otherwise known as tunnel valleys. Here, I continue to use the term ‘tunnel valley’ without genetic implications.

The frozen margin argument was initially proposed by Wright (1973) and focused on basal meltwater from a central, warm-based zone of an ice sheet accumulating behind a cold-based margin where glacier ice is effectively frozen to the bed. As in modern jökulhlaups, the frozen margin, or ice dam, is eventually breached, resulting in a sudden, violent discharge of meltwater which incises the tunnel valleys. Wingfield (1990) suggested tunnel valleys in the central North Sea were initiated by jökulhlaups at the ice margin, but proposed that they continued to form by headward erosion during collapse of the ice sheet, rather than by bankfull flooding alone. Piotrowski (1994, 1997) is one of the few European authors to suggest a catastrophic origin for tunnel valleys in north-west Germany. He concluded that six major tunnel valleys in the area were largely cut by spontaneous discharges during last glacial maximum, instigated by ponded meltwater behind a frozen toe increasing hydrostatic pressure to decouple the glacier from its bed and produce an outburst (Figure 2.7). His work also considered direct glacial erosion as a significant factor in tunnel valley formation, and stressed the effect of reactivation of tunnel valleys during multiple cycles of advance and retreat.

Clayton et al. (1999) also argued for a catastrophic, frozen toe origin for tunnel valleys at the margin of the former Green Bay lobe in Wisconsin. The authors discount a sheet-flood origin for the tunnel valleys as they find no evidence for erosional drumlins in the region, and consider eskers associated with the tunnel valleys to have been deposited subsequently during ‘normal’ subglacial meltwater flow. Following the catastrophic outburst the roof of ice above the tunnel valleys collapsed, focusing supraglacial debris into channel forms which, when the ice melted, provided the hummocky basal deposits now observed along the base of the tunnel valleys.

Recent work by Hooke and Jennings (2006) follows on from the work of Attig et al. (1989) with a quantitative analysis of the probability of ponded meltwater formation behind a ‘frozen’ glacier margin leading to the build up and catastrophic release of meltwater to form tunnel valleys. The authors predict that if Darcian flow through the substrate is insufficient to adequately drain subglacial meltwater, water pressure will
increase to sufficient levels to initiate ponding of meltwater in subglacial lakes beneath an ice sheet. Seepage at the frozen margin (where high water pressures in the soil allow meltwater to emerge through fractures and erode the bed material) initiates piping up-glacier from the ice margin. If the piping is sustained, it may eventually tap the ponded meltwater, leading to an outburst which incises channels into the substrate. Once the reservoir is exhausted the authors suggest that the channel is filled with ice and effectively closed; meltwater then begins to accumulate and will eventually be released catastrophically again along the same channel, resulting in the substantial tunnel valleys observed.

Catastrophic formation theories related to sheet-flooding are typically reliant on the interpretation of a range of landforms, such as drumlins, flutings, erosional marks, and eskers, and are therefore dependant on the acceptance of certain modes of formation for such landforms, particularly in North America (Brennand and Shaw, 1994; Ó Cofaigh, 1996; Benn and Evans, 1998; Clayton et al., 1999). However, the controversies generated by the general discussion of origin for glacial landforms, particularly drumlins, may serve to distract from the question of tunnel valley formation. This is particularly important when considering the genesis of the European tunnel valleys, most of which do not contain obvious examples of features such as eskers and are not linked to nearby drumlin fields or other large scale landform systems indicative of flooding (Wingfield, 1990; Benn and Evans, 1998; Ehlers and Gibbard, 2004; Evans et al., 2005).

Although originating in the sheet-flood model of Shaw (1983), theoretical work by Shoemaker (1992) encouraged the sheet-flood model to be applied to tunnel valleys, initially by Brennand and Sharpe (1993) and Brennand and Shaw (1994) in Canada. Their model relies on the instability of large-scale subglacial sheet-floods beneath ice sheets to induce channelisation and the formation of tunnel valleys which are cut simultaneously in bankfull conditions. Barnett et al. (1998) summarise much of the work carried out on the tunnel valleys of the Oak Ridges Moraine complex in southern Ontario, which have been widely studied in the sheet-flood context. Russell et al. (2003) in their recent sedimentological work on buried tunnel valleys of the Oak Ridge Moraine also opt for incision by catastrophic flooding. In Michigan, a number of works led by Fisher (Fisher and Taylor, 2002; Fisher et al., 2003, 2005) support a collapsed
sheet-flood origin for extensive tunnel valley networks related to the Saginaw Lobe of the Laurentide ice sheet.

Sjogren et al. (2002 p. 41) observed "linked pothole" channel features in otherwise hummocky terrain that they interpret as incipient tunnel valleys, only partially formed. They suggest that the features in Alberta are part of a regional suite of erosional landforms created by a "regional scale event that required the catastrophic drainage of large reservoirs of meltwater" which most likely drained initially as a sheet-flood (Sjogren et al., 2002, p. 54). Beaney and Shaw (2000), Beaney (2002), Rains et al. (2002) and Shaw et al. (2006) also argue for tunnel valleys as part of a landform assemblage related to regional scale flooding beneath the western Laurentide ice sheet in Alberta, Canada. The above authors suggest that the primary cause of flooding was the catastrophic drainage of subglacial Lake Livingstone (Rains et al., 1990).

Catastrophist theories for tunnel valley formation are widely accepted in North America, but regional-scale sheet flooding is still regarded as a very controversial topic, as debated recently by Benn and Evans (2006), Shaw and Munro-Stasiuk (2006), Evans et al. (2006) and Shaw et al. (2006). However, many authors lean towards some of the same conclusions reached by those on the steady-state side of the argument in appreciating that tunnel valley formation may be polygenetic, and that the tunnel valleys we observe today may have been re-used and modified over a number of glacial cycles.

2.3 Tunnel Valley Morphometries and Character

Although most of the tunnel valley studies mentioned above describe the morphology and scale of the landforms, very few works (with the exception of Praeg, 1996, Lonergan et al., 2006 and Kristensen et al., 2007) explicitly undertake quantitative analysis of tunnel valley geomorphology with respect to their formation and relationship to ice sheets. In this work (see Chapter 6) I present the results of the morphological analysis of a large numbers of tunnel valleys (~180) imaged in high resolution 3D seismic reflection data with a combined extent more than ten times greater than that of previous works (Praeg 1996, 2003; Lonergan et al., 2006; Kristensen et al., 2007).

2.3.1 Depths, Widths, and Lengths
Features categorised as tunnel valleys vary in depth from tens to hundreds of metres, with some filled tunnel valleys in the central and southern North Sea described as having depths of greater than 450 m from top of fill to base (Cameron et al. 1989; Praeg, 1996, 2003). Typically, buried European tunnel valley systems have depths within the range of hundreds of metres (Long and Stoker, 1986; Wingfield, 1990; Ehlers et al., 1991; Huuse and Lykke-Andersen, 2000; Kluiving et al., 2003; Ehlers and Gibbard, 2004; Lonergan et al., 2006; Kristensen et al., 2007) although depths of tens of metres are common for isolated or tributary systems on land, such as those described in northern Germany by Piotrowski et al. (1999) and the open systems summarised in Denmark by Jørgensen and Sandersen (2006). With the exception of those tunnels found on the Scotian shelf with depths of around 430 m, the North American Laurentide and Cordilleran systems are generally shallower, displaying internal depths of 10 - 300 m (Loncarevic et al., 1992; Brennand and Shaw, 1994; Ó Cofaigh, 1996; Patterson, 1997).

Depths for tunnel valleys are not, however, consistent along their axes. A distinctive morphological characteristic of tunnel valleys, however they are defined, is a concave-up or undulating longitudinal profile, with the valleys containing overdeepened troughs or scours and lacking a constant down-valley increase in depth, as would be expected in a subaerial fluvial system. Woodland (1970, p. 534) summarises this for Danish tunnel valleys, noting that "the resulting thalwegs are not gently sloping like those of a subaerial stream, but very uneven, with long irregular depressions separated by sills and thresholds". Van Dijke and Veldkamp (1996, p. 328) describe a characteristic tunnel valley system in northwest Europe as having an "irregular base with many thresholds", or as a joined network of individual depressions with multiple start and end points. European studies of tunnel valleys directly comparable to those examined in this thesis depict troughs and sills hundreds of metres in length and up to 200 m above thalweg. As a geomorphological signature, undulating basal profiles provide significant evidence that tunnel valleys were formed subglacially by meltwater under pressure, a view now generally agreed upon by workers in the field (Ó Cofaigh 1996; Huuse and Lykke-Andersen 2000).

Another common morphological characteristic of tunnel valleys is their tendency to display very abrupt start and end points, shallowing from depths of 100 m or greater to
incision surface-level over lengths of < 1-2 km as observed, for example, by Jørgensen and Sandersen (2006). Detailed morphological measurements by Kristensen et al. (2007) reveal steep (up to 16°) end slopes for tunnel valleys in the eastern North Sea. In north American studies, tunnel valley systems associated with the central Laurentide ice sheet in Wisconsin are seen to slope upwards by up to 20 m/km (Clayton et al., 1999). Again, this "startling abruptness" of start and end points (Woodland, 1970, p. 526) is a geomorphological characteristic markedly different from that observed in fluvial systems, which generally display gently decreasing gradients downstream (e.g. < 2° or gradients of 1:1000) (Knighton, 1998).

Tunnel valleys are often reported to be steep sided (up to 55° in Grube, 1983, and 45° in Kristensen et al., 2007) and U-shaped, and many display cross profile asymmetry, where one flank is significantly steeper than the other (Long and Stoker, 1986; Wingfield, 1990; Brennand and Shaw, 1994; Ó Cofaigh, 1996; van Dijke and Veldkamp, 1996; Praeg, 2003). Shallower, less steep (< 5°) valley walls are also observed, although Huuse and Lykke-Andersen (2000) note that in the case of buried features in the North Sea, these are more difficult to image in seismic reflection data and thus less likely to be described as tunnel valleys, although their morphological characteristics are otherwise similar.

Tunnel valley widths of up to 10 km are reported in the southern North Sea and offshore Canada, although it is very likely this is a due to spatial aliasing arising from the >10km wide spacing used in 2D seismic surveys (Cameron et al., 1987). Studies using closely spaced 2D seismic lines, or 3D seismic reflection datasets such as Praeg (1996, 2003), Kluiving (2003), Lonergan et al. (2006), Jorgensen and Sandersen (2006) and Kristensen (2007) generally show buried tunnel valleys of < 6km in width. The majority of tunnel valley systems in northern Europe and North America show widths of 200 m to 4 km (Ó Cofaigh, 1996; Huuse and Lykke Andersen, 2000).

Tunnel valley lengths of up to 130 km are observed in the North Sea, Irish Sea and Scotian shelf (Cameron et al., 1987; Eyles and McCabe, 1989; Loncarevic et al., 1992; Huuse and Lykke Andersen 2000) with lengths of 1-50 km more common on land. It is noted, however, that reported lengths of buried tunnel valleys may be constrained only by the limits of the available datasets. My work based on extensive merged 3D seismic
dataset has revealed the presence of at least two tunnel valleys > 120 km in length (see
Chapter 6).

Width to depth ratio (w:d) is a common measurement used in fluvial geomorphology to
examine process and channel form, and can be related to a number of factors such as
quantify and compare width to depth measurements for modern meandering, incised
and braided channels while Gibling (2006) takes this further by incorporating measures
of width and depth from the subsurface literature to create twelve categories of channel
form and fill. Gibling (2006) incorporates tunnel valley fills into his classification,
placing them under a ‘valley fill’ heading (as opposed to channel fill) based on the
criteria outlined by Fielding and Gibling (2005). Tunnel valley w:d measurements from
eleven studies were found to range between 5 and 50, with the majority between 7 and
20. Figure 2.8 displays these measurements and incorporates further representative w:d
data from tunnel valleys studied in the North Sea by Lonergan et al. (2006), Kristensen
et al. (2007) and Bradwell et al. (2008), as well as width:depth measurements for
meltwater channels in Antarctica (Sugden 1991; Lewis et al. 2006) for comparison.
Although variable, it appears that features classified as tunnel valleys generally display
low width to thickness (W/T) values and form wide, relatively deep channels in
comparison to subaerial fluvial systems.

2.3.2 Planform Geometry

Tunnel valley systems are found to form complex networks which vary in channel
planform from broadly arborescent and convergent, as described by Praeg (1996, 2003)
and shown in Figure 2.9a, to semi-rectilinear or sub-parallel as observed in Michigan
by Sjogren et al. (2002) and shown in Figure 2.9b. Many tunnel valley networks are
described as ‘anastomosing’, a typical example of which are those associated with the
Oak Ridge Moraine in southern Ontario, examined by Brennand and Shaw (1994),
Barnett et al. (1998), and Russell et al. (2003), and shown in Figure 2.9c. However, this
planform classification is not straightforward in application to subglacial features such
as tunnel valleys.

Within fluvial geomorphology, anastomosing channels are categorised as a sub-type of
anabranching channels, those which diverge or bifurcate (i.e. anabranch) and then rejoin
downstream to give rise to multi-channel streams with intervening islands. The anabranching category fits into a larger channel classification continuum concept ranging from straight to meandering to braided (Schumm, 1985; Knighton and Nanson, 1993; Rosgen, 1994; Knighton, 1998) and differs from truly braided channels in that each anabranching channel acts as a discrete (but interconnected) conduit, rather than a single channel diverted around obstacles. Schumm (1985) and Rosgen (1994) provide a thorough summary of channel classifications.

In the southern half of his study area, Praeg (1996, 2003) mapped arborescent systems of tunnel valleys converging to the south along seven fairly evenly spaced axes. Within an area of 3D seismic reflection data coverage he found two occurrences of anabranching channels, but found the pattern to be a result of subsequent incision of younger valleys to the north, resulting in ‘apparent anastomosing’.

More recent high resolution work with 3D coverage from TEM surveying onshore in Denmark and from 3D seismic reflection data in the Danish North Sea shows that much of the complexity in planform is also due to several generations of tunnel valleys cross-cutting and overprinting. Within a single generation of tunnel valleys, the Danish onshore (Jørgensen and Sandersen, 2006) and offshore (Kristensen et al., 2007) 3D studies show simple branching geometries with largely straight reaches. Lonergan et al. (2006) found some anastomosing patterns over distances of 5 to 10 km within two individual generations of tunnel valleys out of four.

Work by Catania and Paola (2001), modelling the behaviour of channels in a sand box under glass, is potentially useful in considering the planform geometry of tunnel valleys formed under pressure. Over time, they found that channel systems initiated in a pressurised system displayed higher braiding intensity and variability in flow direction than ‘free-surface’ (subaerial) equivalents, as discharge was increased. Lateral pressure gradients appeared to play a major role in controlling braiding patterns, as bankfull overflow was prevented by a rigid lid; flow was instead driven laterally within the drainage system at high angles to force fresh incision of new channels. Initiation of channels by overflow and avulsion, as is typical in fluvial systems, was prohibited. Instead, complex braided and anastomosing patterning formed under pressure, confirming the viability of complex braided channel formation beneath ice, at least at
the centimetre scale of sand box experiments. Flow-direction measurements for pressurised systems were widely spread in comparison to 'free-surface' experiments, indicating high levels of sinuosity and variable directionality of the channel networks, a common feature of many tunnel valley systems. Figure 2.10 shows the result of one of the pressurised experiments showing an extremely complex planform comparable to some of the tunnel valleys systems described in Figure 2.9.

Thus, tunnel valleys may be observed both in networks and as individual, relatively isolated features such as those described by Patterson (1997) in Wisconsin and Rains et al. (2002) in Alberta, or the independent, low-sinuosity, non-branching channels observed by Kristensen et al. (2007) in the Danish North Sea. Apparent complexity and anabranching in plan form may also relate to the limits of seismic resolution and aliasing.

2.3.3 Associated Landforms

Eskers and other glacial landforms such as drumlins, flutes and fans are commonly associated with unfilled (or partially filled) tunnel valleys in North America (for example Christiansen, 1987; Mooers, 1989; Booth and Hallet, 1993; Brennand and Sharpe, 1993; Brennand and Shaw, 1994; Pair, 1997; Barnett et al., 1998; Clayton et al., 1999; Evans et al., 1999; Fisher et al., 2002, 2005; Rains et al., 2002; Russell et al., 2002; Sjogren et al., 2002). Landform assemblages of eskers, kames, tunnel valleys, fans and recessional moraines are used to mark the extent (and retreat) of the central Laurentian ice sheet from the west, in central Minnesota (Mooers, 1989; Wright, 1973; Patterson, 1997) to the eastern Lake Michigan lobe (Clayton et al., 1999). Such features are noted less frequently in European examples, although they may be more common in central and eastern Europe where esker-tunnel valley associations are mentioned by Grube (1983) and Piotrowski (1994) in northern Germany, and by Pasierbski (1979) and Fard et al. (2007) in Poland.

As subglacially formed landforms, the presence of eskers within tunnel valleys implies a subglacial environment post-formation of the tunnel valleys, used by many authors to support a subglacial origin for the tunnel valleys themselves and to provide relative ages for the formation of the tunnel valleys and eskers (Mooers, 1989; Brennand and Shaw, 1994; Brennand, 1994; Sjogren et al., 2002; Fisher et al., 2005). In general, the authors
above are advocates of a catastrophic flood origin for the tunnel valleys, with eskers formed during the final waning flow, although the difference in scale between eskers and tunnel valleys is used by Clayton et al. (1999) and Sjogren et al. (2002) to suggest formation under very different hydrological conditions.

Joint esker/fan/tunnel valley systems have been used by Christiansen (1987) and Mooers (1989) to suggest that erosion of tunnel valleys was contemporaneous with glaciofluvial deposition of the eskers and fans, a view furthered by Praeg (1996; 2003) in his ‘backfilling’ hypothesis. Praeg (1996, p. 174) goes as far to say that “tunnel valleys and eskers record the same basic processes of sub-marginal erosion and deposition during glaciation, but the geological expression of those processes changes due to the nature of the glacier bed”.

In terms of morphology, eskers described within tunnel valleys systems range from small features less than 500 m long, approximately 10 m in height and 50 m wide (Fisher and Taylor, 2002) to dendritic systems up to 70 km in length and up to 100 m in width (Brennand and Shaw, 1994).

Drumlins and drumlin fields associated with tunnel valleys systems, such as those on the Oak Ridge Moraine system in Ontario (Barnett et al., 1998), in Alberta (Rains et al., 2002) and in Michigan by Fisher et al. (2005), are also often interpreted as erosional subglacial features, formed during sheet-flooding beneath ice prior to tunnel valley initiation. Drumlins are varied in their morphology, generally described as elongate, humped deposits < 10 km in length and up to 200 m in width, although often smaller (Benn and Evans, 1998). Small-scale erosional s-forms and spindles with dimensions of < 10 m are recorded by Pair (1997) within tunnel valleys in New York.

Metre-scale gravel transverse ridges and bars are documented on the floor of tunnel valleys by Brennand and Shaw (1994), Fisher and Taylor (2002), and Fisher et al. (2005), and are interpreted as having being deposited during waning flow immediately after erosion of the tunnel valleys by catastrophic flooding. As relatively large-scale features formed from coarse, well-sorted gravels with strongly directed palaeocurrents, the cross-beds in these deposits suggest powerful flow.
2.4 Tunnel Valley Infill

2.4.1 Pleistocene Tunnel Valleys

The wide variety of features described as tunnel valleys, their varying location, the possibility of more than one formation mechanism for their origin and evolution, and varying post-formation environments has led to a situation in which there is no typical fill pattern or facies model for the sediment found within filled or partially filled tunnel valleys. Although it is a tempting notion, there is as yet no proven link between tunnel valley fill and formation. As O'Cofaigh noted in his 1996 (p. 15) summary of tunnel valley formation the "sedimentary sequence infilling a tunnel valley is insufficient evidence from which to deduce the process of valley incision". Furthermore, analysis of buried tunnel valley fill is reliant on geophysical methods and often widely spaced boreholes.

The presence of till is described within a number of tunnel valley fills (Cornwell and Carruthers, 1985; Vaslet et al., 1990; Loncarevic et al., 1992; Piotrowski, 1994; Dobracki and Krzyszkowski, 1997; Piotrowski et al., 1999; Eyles and de Broekert, 2001; Hirst et al., 2002; Kluiving et al., 2003; Jørgensen and Sandersen, 2006), and implies direct glacial contact and the presence of (sometimes long lasting) ice within the valleys. Till is often identified locally on the sides of valleys, or in the deepest parts of the base and may be present at a number of levels. Piotrowski (1994), for example, correlates three layers of till within a complex tunnel valley fill in onshore northwest Germany to the three most recent Pleistocene glaciations. Rafted tills are identified within tunnel valleys by Ehlers and Linke (1989) and Piotrowski (1994) are described as having undergone glaciotectonic modification.

Studies of North Sea and northern European tunnel valleys have identified a two or tri-partite fill identified by seismic facies and consisting of a chaotic basal unit overlain by one to two or more layered or structured units as in Figure 2.11a (Long and Stoker, 1986; Cameron et al., 1987; Long et al., 1988; Ehlers and Linke, 1989; Balson and Jeffrey, 1991; Praeg 1996, 2003; Huuse and Lykke-Andersen, 2000; Jørgensen and Sandersen, 2003, 2006; Kluving 2003, Lonergan et al., 2006; Kristensen et al., 2007). Limited borehole data from these examples indicate a coarse glaciofluvial sand and gravel lag, overlain by glacio-fluvial sands and clays, and topped by glaciolacustrine -
glacimarine sediments. Slumping of sediment from the side walls of tunnel valleys is proposed as an alternative to a glacial till source for the basal chaotic unit (Smith, 1985; Long and Stoker, 1986; Long et al., 1988).

As discussed in Section 2.2.3, Praeg (1996, 2003) found evidence for large-scale (extending up to 20 km along the axis of tunnel valleys and up to 400 m deep) axially downlapping clinoform features in the lower seismic unit (previously interpreted as unstructured by Cameron et al., 1989, amongst others) of buried tunnel valleys in the southern North Sea. The clinoform fill unit was found to be largely sand-dominated with some locally derived gravel and reworked microfossils. The upper unit of the tunnel valley fill comprised sub-horizontal reflectors which were found to contain glacilacustrine and marine muds. Evidence for backfilling structures to this scale had not previously been reported.

Lonergan et al. (2006), in their work using 3D seismic reflection data, found many of the tunnel valleys in their study to contain three distinct seismic units. A discontinuous basal unit up to 25 m thick, displaying moderate to high amplitudes, was found in the deepest part of some of the tunnel valleys. This was overlain by a middle unit containing wedge-shaped packages characterised by continuous dipping moderate reflectors and thickest (up to 40 m) at tunnel valley junctions. The uppermost unit comprised low-amplitude, sub-horizontal reflectors which drape the tunnel valleys completely. A lack of borehole evidence in the study did not allow for the lithological characteristics of the seismic units to be finalised, but the authors infer lithofacies associations by correlations with previous works in the North Sea (Cameron et al., 1989; Kluiving et al., 2003; Praeg, 2003). As such, they interpret the basal unit as either a gravel lag or till, deposited immediately after the initial excavation of the tunnel valleys. The middle unit wedges were also deposited in subglacial conditions, with sedimentation either by erosion upstream or by reworking of underlying material. The uppermost drape package was considered to be deposited in quiet conditions, most likely glaci-lacustrine to distal shallow marine environments.

Work by Kluiving et al. (2003) is particularly important when considering the fill of buried tunnel valleys in the North Sea area, as it is the only study reported in the region that linked an onshore and offshore 2D seismic profiling campaign with targeted
drilling of two boreholes and wire line logs for a single tunnel valley system. The authors find a conspicuous transition from clays to sands at the erosional base of the tunnel valleys. A basal unit 20 – 45 m in thickness, comprised of coarse sands and gravels (with 2 – 5 m thick clay/sand/gravel diamicton sequences at their base) is seen in both boreholes and as a distinctive high amplitude package at the base of all tunnel valleys in their dataset. The coarse nature and presence of reworked clays in the basal unit is used to suggest direct ice contact during formation of the unit and, in particular, subglacial deformation due to grounded ice in the tunnel valley.

Overlying the basal units are between two and six sandy fill packages displaying tabular geometries in seismic profile with varying seismic amplitude and thickness. These features correspond to thick (up to 150 m) intercalated sands with complex fining-upwards and coarsening-upward and sawtooth patterns. The varying scales of coarsening to fining patterns observed (from millimetre scale to greater than 10 m) are used to suggest deposition in fluctuating energy environments. All marine profiles in Kluiving et al. (2003) show high amplitude reflectors overlying the sandy middle fill units, marking the distinction between tunnel valley fills and surrounding sediment. The onlapping units comprise coarse sands with an increasing percentage of clay, and all display fining up sequences, indicative of increasing shallow marine conditions and increasing distance from the ice front respectively.

Kluiving et al. (2003) suggest deposition of tunnel valley fill in predominantly water-based settings, ranging from high energy glaciofluvial channels to quiet proglacial lacustrine environments. Coarsening and fining patterns are used to provide evidence for cyclical variations in current and energy systems, and the preservation of thin (mm scale) clay layers and fining sequences suggest deposition over time and preclude catastrophic flooding. In conclusion, Kluiving et al. (2003) consider a dynamic but gradual deposition of the tunnel valley infill, reflecting ice advances during an overall period of retreat. Further work by authors such as Jørgensen and Sandersen (2006) support these findings, demonstrating complex fills within complex systems of tunnel valleys as in Figure 2.11b.

Onshore studies of tunnel valley fill tend to reveal similar fill patterns, but at smaller scales. Eyles and McCabe (1989) find fill sequences comparable to those discussed
above, but with each unit being less than 10 m thick, in an exposed Quaternary infilled tunnel valley system near Dublin Bay, part of a larger tunnel valley system in the Irish Sea. They suggest a depositional process model with fluvioglacial channel lag responsible for basal deposits, followed by glacimarine deposition by sediment gravity flow for the middle part of the fill and overlain by muddy sediments deposited during isostatic uplift and marine transgression. Their study stresses the importance of rising sea level due to isostatic rebound as a means to uncouple an ice sheet from its bed and promote the glacimarine fill of tunnel valleys cut subglacially in submarine conditions.

The Laurentian North American tunnel valleys are generally only partially filled, and are often described as containing thick layers of coarse sands and gravels at their base (Christiansen, 1987; Brennand and Sharpe, 1993; Brennand and Shaw, 1994; Davies and Austin, 1997; Barnett et al., 1998). As with onshore tunnel valleys in North Africa and in Europe, fill sequences are generally an order of magnitude smaller than those observed offshore, with units < 100 m thick. Gravel fill features are generally interpreted to be indicative of high discharge glacio-fluvial flow during deposition, and those displaying cross-bedding and other palaeocurrent indicators are used to support the theory of tunnel valley formation by catastrophic flooding (Brennand and Shaw, 1994; Barnett et al., 1998).

### 2.4.2 Pre-Quaternary Tunnel Valleys

Interpretations of well-exposed Ordovician tunnel valley infill in the Middle East and Northern Africa by authors such as Vaslet (1990), Abed et al. (1993), Hirst et al. (2002) and Le Heron et al. (2004, 2006) also provides evidence for prolonged tunnel valley infilling under varying environmental conditions ranging from glacimarine fan systems to direct till deposition by basal glacial ice, but again at a smaller scale than those observed offshore. Hirst et al. (2002) found a basal unit consisting of local slumped blocks several metres across and coarse grained sandstones showing cross-bedding and current ripples, interpreted as a glaciofluvial deposit, with the blocks a result of supraglacial debris or slumping of the valley walls. Overlying the basal deposits are up to 10 metres of extensive muddy sandstone units with little lithological variation and no sedimentary structure, which are interpreted as stacked density flows, with sandier units to the top interpreted as debris flows and turbidites. Graptolites, indicative of a fully glacimarine environment, are found towards the top of the turbidites and the unit is
interpreted to have formed beneath a grounded ice sheet on the continental margin with marine conditions becoming more influential as the ice sheet retreated.

In Saudi Arabia, Vaslet (1990) also describes Ordovician tunnel valley systems containing a three-fold fill. A basal tillite unit contains gravels and boulders displaying striated surfaces, and is interpreted as morainic till modified by periglacial processes. The basal unit is topped by a boulder clay composed of dark green siltstone with a varying proportion of dropstones ranging in size from gravel to boulders, which is interpreted to have been deposited during a quiet marine or lacustrine environment during a period of ice retreat. This middle unit tops the tunnel valleys and shows evidence of varves and local readvance in the form of tillites, and becomes dominated by glacimarine sandstones towards its top. The upper part of the fill displays fine-grained sandstones containing thin layers of laminated clay and periglacial structures, marking a return to cold, shallow marine conditions.

A reliance on 2D seismic profiles and a lack of borehole information for offshore tunnel valleys hinders analysis of their fill, and as yet, there is no commonly accepted facies model for tunnel valleys. Work using 2D seismic sections has shed much light on tunnel valley architecture but lacks the resolution required to image and resolve the complex vertical and lateral variation in lithology known to characterise the fill of offshore buried tunnel valleys such as that observed by Kluiving et al. (2003). North African and Arabian studies, such as those by Hirst et al. (2002), probably provide the most complete fill facies analysis available, but at a significantly smaller scale than those observed offshore, making direct comparison problematic. In Chapter 7 the results of seismic facies analysis of an unprecedented number of buried tunnel valleys in the central North Sea are presented and compared to other similar studies in the regional area.

2.5 Conclusion and Rationale

Previous research on tunnel valleys emphasises the diversity and complexity of their morphology and fill, and highlights a number of areas of interest to this study. Their method of formation has in many cases dominated the tunnel valley literature, with fundamental differences related not only to tunnel valleys themselves and their
associated features such as eskers and drumlins, but also to differing models of glacial hydrology and substrate properties.

Recent work in north-west Europe using similar techniques as those employed in this study are beginning to move away from a bipolar (steady state versus catastrophic) view on their formation and consider instead a polygenetic origin for tunnel valleys (Huuse and Lykke-Andersen, 2000; Kluiving et al., 2003; Jørgensen and Sanderson, 2006; Lonergan et al., 2006; Kristensen et al., 2007). Significantly, these works are also strong supporters of tunnel valley systems as palimpsest features, composed of multiple generations of cross-cutting tunnel valleys which are re-used and modified within and between glacial cycles. This complex view of tunnel valley formation and modification is one for which my work finds ample evidence (see Chapter 5), and is also of interest when considering the dynamics of ice sheet cover in the North Sea during the Pleistocene.

Other factors which emerge in a review of tunnel valley literature include the importance of substrate and its associated drainage properties, the relative position of ice margins to tunnel valleys, and the thickness and dynamics of the overriding ice sheet. By carrying out extensive quantitative analysis of the morphology and fill of ca. 180 tunnel valleys in the central North Sea, this work makes progress in addressing these topics.
Figure 2.1 Distribution of Quaternary tunnel valleys in northwest Europe with disputed Pleistocene ice limits from Huuse and Lykke-Andersen (2000, p.1237). The location of the Silver Pit and Devil's Hole seabed deeps are shown as SP and DH respectively. The study area investigated in this work is shaded in grey.
Figure 2.2 Distribution of tunnel valley studies in North America
Figure 2.3 Distribution of tunnel valley studies in north Africa, the Middle East and Australia (insert). Approximate extent of Late Ordovician grounded ice sheet shown as dashed line (Le Heron et al., 2004). SP is location of Ordovician South Pole as in Sutcliffe et al., (2000).
Chapter 2: Tunnel Valley Background

Figure 2.4 Longitudinal section down the Brett Valley from Boswell (1913, p.600) showing an undulating base as in modern studies of tunnel valleys. The valley is cut into chalk and filled with sand, gravel and boulder clay.
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Figure 4.6a Tunnel valley initiation by deformation in unconsolidated sediment i) Saturation of aquifer initiates piping which develop into tunnel valleys. ii) R-channel formation of tunnel valleys where water pressure in high discharge channel ($P_w$) is less than pressure from ice ($P_i$) enhances sediment creep into channel. sediment then removed by meltwater to initiate tunnel valley development. Figure redrawn from O’Cofaigh (1996, p. 7).

Figure 2.6b Distinction between bankfull tunnel channels (A) and tunnel valleys (B and C) as defined by Clayton et al. (1999). Figure redrawn from Clayton et al. (1999, p. 72).
Fig. 16. Schematic representation of major mechanisms controlling subglacial meltwater dynamics during the first (1—3) and the second (3-5) Weichselian ice advances. (1) Ice sheet moves up-slope from the Baltic Sea depression onto the Saalian highlands. A meltwater collector develops subglacially, causing a rapid advance of a low-profile ice sheet. Drainage of the water collector is hampered by hydraulic contact to a higher-altitude proglacial basin (Piotrowski, 1993b). (2) Ice margin overrides the permafrost which then prevents the drainage of subglacial meltwaters and causes a water-pressure buildup. (3) As the ice margin retreats from the outermost extent and the unfrozen bed is exposed, a rapid outburst of subglacial waters occurs and erosion by a high-pressure water jet initiates the tunnel-valley formation. (4) During the second Weichselian ice advance the tunnel valley is a major subglacial spillway probably active in a series of short, catastrophic outbursts separated by periods of pressure buildup. Finally, a complete drainage of the subglacial water reservoir further up-ice occurs. This in turn causes lowering of the ice sheet onto its bed (5) and thus an increased basal friction, which could have been responsible for the progressively lesser extents of the subsequent Weichselian advances. 1 = ice-movement direction; 2 = porewater and basal meltwater flow lines. Figure not to scale.

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Chapter 3: Regional Background

3.1 Introduction and Study Area

The study area referred to in this work is located in the central part of the UK sector of the North Sea extending between approximately 56°N and 59°N and 1°W to 2°E (Figure 3.1). Water depths in the region average between 90 and 150 m, deepening towards the Norwegian Channel to the east.

The North Sea basin developed subsequent to the mid-Jurassic rifting which initiated the formation of the N-S trending Cretaceous Central Graben (Caston, 1977; Nielsen et al., 1986). Post-rift subsidence allowed for the accumulation of up to 3000 m of Cenozoic sediment; thick chalk beds deposited during the Cretaceous being replaced by siliclastic input from Scandinavia and mainland Europe after Palaeogene times (Cameron et al., 1987; Ziegler, 1990; Gatilff et al., 1994; Jordt et al. 1995; Fyfe et al., 2003). Oligocene sedimentation was dominated by deltaic and pro-deltaic systems originating from southern Scandinavia and prograding towards the southwest. These were gradually replaced by westwards and northwest prograding sediments from European delta systems during Miocene/Pliocene times. Mid-to-late Miocene uplift of the basin margins enhanced rapid subsidence and fill during the Pliocene and Pleistocene (Cameron et al., 1987; Fyfe et al., 2003) with up to 1000 m of Quaternary sedimentation estimated for the central North Sea Basin (Caston 1977; Gatilff et al., 1994; Fyfe et al., 2003; see Figure 3.1).

Towards the western edges of the central North Sea Basin (generally west of 1°W), Quaternary sediments are less that 50 m in thickness and lie unconformably on folded Palaeozoic and Palaeogene sediments (Cameron et al., 1987; Gatilff et al., 1994). Towards the centre of the central North Sea basin, the base of the Quaternary succession is less well-defined, but it is considered to exceed 850 m in thickness (Gatilff et al., 1994). Basin-wide seismic profiles indicate the cessation of tectonic influence north of 55°N after Palaeogene times (Cameron et al., 1987), although salt movement may have locally affected the oldest Pleistocene sediments between 56°N and 57°30'N (Gatilff et al., 1994). Halikinetic structures are more common towards the southern part of the central North Sea (south of 54°N) and control fault zones which influenced
sedimentation rates in the area until the middle Pleistocene (Balson and Cameron, 1985; Cameron et al., 1987).

The Mid to Late Pleistocene succession of the North Sea is dominated by glacigenic sediments which reflect repeated glaciations during this time (Sejrup et al., 2005). Traditionally, three glaciations dating from the Mid-Pleistocene onwards have been recognised within the North Sea sediments, largely extrapolated from the onshore Quaternary stratigraphy of Scandinavia, Germany, the Netherlands and the UK and termed the Elsterian, Saalian and Weichselian stages in the European nomenclature (Ehlers and Gibbard, 2004, and references therein). In the UK the equivalent stages are known as the Anglian (Elsterian) and Devensian (Weichselian). This stratigraphy is correlated with the marine isotope stages (MIS) and a number of palaeomagnetic events including the Bruhnes-Matuyama reversal at 0.78 Ma identified by Stoker et al., (1983) and summarised in Figure 3.2.

Dense networks of buried tunnel valleys have been recognised within the Pleistocene succession of the North Sea for some time and are correlated with a regionally important erosion surface which marks the transition from non-glacial to glacial conditions from the Mid-Pleistocene onwards, and, more specifically, to the three Mid-Pleistocene ice sheets described above (Stoker et al., 1985; Cameron et al., 1987; Balson and Jeffery, 1991; Ehlers and Wingfield, 1991). The buried tunnel valleys which are the focus of this work are found wholly within poorly lithified Quaternary sediments at least 100 m thick (see Figure 3.1, Figure 4.4) and generally at less than 350 m beneath seabed. A number of salt domes were found within the study south 57°N but do not affect the top 500 m of sediment (for further discussion see Chapter 7, Figure 7.12). Local controls on tunnel valley distribution (such as variation in substrate and salt tectonics) are therefore considered to be insignificant in comparison to the basin-wide influence of the Pleistocene ice sheets which formed the tunnel valleys.

A solid chronological framework for the Quaternary stratigraphy of the central North Sea is lacking for a number of reasons. Firstly, until recently, the majority of work on the glacial history of the region has been reliant on 2D seismic data and a limited number of boreholes to interpret a multitude of variable, laterally complex glacigenic sediments and landforms. By nature, 2D seismic data do not provide the spatial
resolution needed to image the geometry of low amplitude but laterally extensive geomorphological features such as megascale glacial lineations and ice scour surfaces which would assist in the reconstructions of past glaciations.

Further problems are encountered due to a lack of chronological control, related not only to the relative paucity of shallow stratigraphic boreholes in the area, but also to well-known problems associated with dating Quaternary sediments such as lack of suitable fossil material, and the effects of reworking and re-deposition (Carr et al., 2006). Björck et al. (2003) highlight some of the problems associated with offshore $^{14}$C dating in the northern Atlantic and Norwegian Sea, including well-known marine reservoir effects and dilution due to increased melting during Heinrich events, which lead to errors of more than ± 1100 years for the dating of sediments derived from radiocarbon methods. Previous dating controls on the glacigenic sediments in the region based on radiocarbon ages sediments in the region (Sejrup et al., 1987; King, 1991; Sejrup et al., 1994) must be reconsidered in this light.

A final problem concerning the glacial history of the North Sea is related to recent investigations by Lonergan et al. (2006), Graham (2007) and Kristensen et al. (2007), which provide morphological evidence to suggest a more complex, polygenetic history of glacigenic sedimentation in the North Sea. Lonergan et al. (2006) and Kristensen et al. (2007), for example, show that tunnel valleys in the region comprise polyphase cross-cutting networks which are likely to have been influenced by a number of glacial and marine processes. The above factors, combined with a poor understanding of much of the genetic origin of the glacial sediments in the sequence, requires the revision of the original stratigraphic framework in the area (Stoker et al., 1985; Sejrup et al., 1987, 1994; Cameron et al., 1987) as discussed below.

### 3.2 The Stratigraphy of the North Sea

Work on establishing the Quaternary stratigraphy in the UK sector of the North Sea was largely carried out using a combination of shallow cores and 2D seismic profiles from 1967 to the early 1990s (Flinn, 1967; Jansen, 1976; Caston, 1977; Holmes, 1977; Thomson and Eden, 1977; Balson and Cameron, 1985; Stoker and Bent, 1985; Stoker et al., 1985; Cameron et al., 1987; Sejrup et al., 1987, 1991, 1994; Long et al., 1988; Andrews et al., 1990; Jeffery, 1991; Johnson et al., 1993; Gatli ff et al., 1994). Stoker et
al's (1985) stratigraphic framework was used as the basis for the majority of subsequent studies in the central North Sea but is hampered in its scope by a reliance on 2D seismic data and relatively few cored boreholes. Recently, however, with the use of micromorphological techniques, 3D seismic reflection datasets, and detailed bathymetric surveys have provided a more complex picture of the chronological and sedimentary structure of the North Sea (Carr et al., 2000, 2006; Sejrup et al., 2000, 2005; Lonergan et al., 2006; Jørgensen and Sandersen, 2006; Kristensen et al., 2007; Graham, 2007, Graham et al., 2008, Bradwell et al., 2008).

Figure 3.3a is a fence diagram illustrating the central North Sea stratigraphy based on the 2D seismic profiles acquired in the late 1970s and early 1980s based on the work of Stoker et al., (1985). The location of the profiles in the fence diagram can be seen in Figure 3.3b, on a BGS seabed Quaternary Geology map north of 56°N (Gatliff et al., 1994). Buried and surface tunnel valleys are apparent in both interpretations, and are associated with the nine formations defined by Stoker et al., (1985) for the central North Sea and discussed in this work (Figure 3.3, Figure 3.4).

3.2.1 BGS Stratigraphy

3.2.1.1 Non-glacial formations

The oldest Quaternary unit in the central and northern areas (north of 56°N and south of 62°N as in Figure 3.3) of the North Sea is recognised in the UK sector as the Aberdeen Ground Formation, (Stoker et al. 1983, 1985). The formation is regionally extensive, at least 200 m thick in the central part of the basin (where its base has yet to be defined) and can be seen to thin towards the western margin of the basin to a thickness of some tens of metres (Figure 3.3a) The formation is characterised seismically by high-amplitude laterally continuous reflectors which occur up to 60 m apart, giving a strongly bedded appearance (Holmes, 1977; Cameron et al., 1987). Second order reflections are seen towards the southern margins of the North Sea dipping to the NW, documenting delta expansion northwards from mainland Europe. Borehole analysis reveals that the majority of the Aberdeen Ground Formation comprises bioturbated marine clays with intermittent beds of sand, indicative of formation in a shallow marine setting with episodic instances of non-deposition marked by erosional surfaces (Cameron et al., 1984; Stoker and Bent, 1987).
The Brunhes-Matuyama magnetic boundary, dated at 780 000 ± 5000 years was found within the Aberdeen Ground Formation in ten BGS boreholes across the central North Sea, confirming the presence of early Middle-Pleistocene ages of the lower parts of the Aberdeen Ground Fm (Stoker et al., 1983). The Jaramillo event within the Matuyama Reversed epoch is found deeper within the Aberdeen Ground beds in five BGS boreholes and is dated at ca. 890 000 to 950 000 years B.P. Stoker and Bent (1985) consider the oldest parts of the Aberdeen Ground Formation to be Tiglian in age (Figure 3.4).

Towards the top of the Aberdeen Ground Formation, in central and eastern parts of the basin borehole cores found microfossils indicating a change towards colder, glacimarine conditions, with dropstones and matrix supported clasts in the associated sediments (Stoker and Bent, 1985; Cameron et al., 1987; Long et al., 1988). This upper unit, which is considered to be equivalent to the ‘Cromerian Complex’ stage in the Netherlands, (Figure 3.2, 3.4) is divided into four lithofacies by Stoker and Bent (1985), the oldest of which is found to contain a local subglacial till up to 3 m in thickness near the Forth approaches (borehole 81/26, see Figure 3.1; Stoker and Bent, 1985; Sejrup et al., 1987; Andrews et al., 1990). Towards the centre of the basin, Stoker and Bent (1985) also find evidence for proximal to distal glacimarine sediments in the upper parts of the Cromerian Complex, confirming the presence of an early Mid-Pleistocene glaciation in the North Sea which preceded the onset of the Elsterian (MIS 12 -10) glaciation.

In the southern UK sector of the North Sea, (i.e. south of the study area, Figure 3.1), deltaic-related formations dominate the Early to Mid-Pleistocene sequences of the North Sea basin, and up to seven formations were defined by Cameron et al. (1987, 1992). The uppermost seismic facies display nearshore and delta-top characteristics, suggesting deposition northwards from the delta front which lay to the south of the UK sector of the North Sea (Cameron et al., 1987, 1992). This part of the pre-glacial succession of the southern North Sea is known as the Yarmouth Roads Formation, which extends eastwards to the Dutch sector with a thickness of up to 130 m (Cameron et al., 1992). The deltaic units are generally grouped together and considered as laterally equivalent to the Aberdeen Ground Formation to the north (Gatliff et al., 1994).
North of 58°N (i.e. north of most of the study area, Figure 3.1), pre-glacial Pleistocene sediments have been mapped as the Shackleton Formation (Stoker et al., 1983; Cameron et al., 1987), and are characterised seismically by high amplitude, laterally persistent reflections to the north becoming more diffuse with lower amplitudes to the south. The unit thins westward from a maximum of 100 m, and comprises well-sorted sand at its base, passing upwards into sandy clays with little microfossil evidence for climatic deterioration as in the Aberdeen Ground Formation (Cameron et al., 1987). However, the Shackleton Formation sediments also display a reversed magnetic polarity, placing them in the late Early-Pleistocene and thus suggesting that they are laterally equivalent to the Aberdeen Ground Formation.

3.2.1.2 Glacial Sequences

The top of the Aberdeen Ground Formation is defined by a regionally extensive unconformity comprising several generations of valley incisions which represent the complex networks of buried tunnel valleys studied in this work (Figure 3.3a). The older work based on 2D seismic profiles identified three generations of tunnel valley incision in cross-profile, separated by interglacial marine sediments, which were correlated with the three accepted glaciations of the mid to late Pleistocene in northwest Europe (Stoker and Bent, 1985; Stoker et al., 1985; Cameron et al., 1987). Overlying the tunnel valley erosion surfaces are a number of Mid to Late-Pleistocene stratigraphic units associated with the repeated glaciations of the central North Sea up until the Holocene. Five of the units, identified as the Ling Bank, Fisher, Coal Pit, Swatchway and Forth formations are seen to fill tunnel valleys in the central North Sea (e.g. Figures 3.3 and 3.4).

The majority of the tunnel valleys in the central North Sea are described as being filled by the Ling Bank Formation, which reaches local thicknesses of greater than 100 m within valleys, and is either absent or forms drape packages tens of metres in thicknesses outwith the tunnel valleys. The formation is acoustically complex with evidence for bedded, chaotic and transparent reflections within the tunnel valley fill (for more see Section 2.3.3). King (1991) found evidence for till which could be correlated with a chaotic basal seismic unit in one borehole (BGS 77/02, see Figure 3.1 for location), while other cores show the formation to be largely composed of fine-grained sands with occasional clay horizons and some shelly pockets (Stoker et al., 1985). The presence of a rich temperate dinoflagellate flora in the lower parts of the type location
BGS borehole 81/34, for location see Figure 3.1) suggests initial deposition during an interglacial period, with evidence for colder conditions towards the top of the formation. Stoker et al. (1985) and Cameron et al. (1987) originally interpreted a Holstenian age (MIS 9, Figures 3.2, 3.4) for the unit, with evidence for colder conditions towards the top of the formation indicating the onset of the Saalian (MIS 8-6) glaciation. However, Knudsen and Sejrup (1993) suggest that, although the middle section of the formation corresponds to the Holstenian interglacial, a thin lower section in the same borehole is older, deposited either during an Elsterian interglacial or in the Cromerian Complex. Recent work by Lonergan et al. (2006) in the central North Sea provides strong evidence for multiple episodes of glaciation as responsible for the incision and fill of the tunnel valleys in the region, which also precludes a solely Holstenian age for the Ling Bank Formation. Graham (2007) suggests instead that the formation reflects multiple episodes of deposition during the Elsterian and Saalian glaciations, up until the Eemian interglacial (MIS 5e).

Overlying the Ling Bank Formation and Aberdeen Ground Formation is the Fisher Formation, which crops out extensively at seabed north of 57°N and east of 0°, where it is incised by tunnel valleys filled with the Coal Pit and Forth Formations (Figure 3.3). Locally, where it fills tunnel valleys beneath the seabed, its reaches up to 90 m in thickness, but otherwise it occurs as a relatively thin (< 20 m) flat-lying interval. It displays distinctive parallel sub-horizontal reflections, and comprises interbedded fine-grained sand and stiff muds and is interpreted as having been deposited in a shallow-marine environment, possibly related to marine transgression of the North Sea during an interstadial (Stoker et al., 1985). Kundsen and Sejrup (1993) allocate a Saalian age to the formation from foraminifera within a single borehole (BGS 81/34, see Figure 71 of Gatiliff et al., 1994).

The Coal Pit Formation is distributed extensively throughout the central North Sea and reaches thicknesses of up to 120m where it can be seen to fill shallower tunnel valleys considered Saalian in age (Stoker et al., 1985; Cameron et al., 1987; Gatiliff et al., 1994). Its acoustic signature is described as variable, switching between transparent or chaotic packages to relatively continuous high amplitude reflections, and the formation is characterised by interbedded sands and muds at its base, and stiff glacimarine clays towards its top (Stoker et al., 1985). The age of the Coal Pit Formation is not clear, but
in general, it is considered to have been deposited after the Saalian glaciation (MIS 8-6, Stoker et al., 1985), with its upper parts deposited and modified during the Weichselian glaciations (MIS 5d – 2) (Stoker et al., 1985; Sejrup et al., 1994). Recently, Carr (2006) has found micromorphological evidence to suggest some of the Formation was modified by glacial activity during MIS 4.

Relatively flat lying Weichselian deposits of up to 20m in thickness are found to overlie the upper surface of the Coal Pit Formation and are referred to by Stoker et al. (1985) in the Witch Ground area of the central North Sea as the Swatchway Formation (Figure 3.3, 3.4). In seismic data, the Swatchway Formation appears transparent with some layering in places, and displays a strongly irregular geometry. The work of Graham (2007) and Graham et al. (2007) show its upper surface to have been eroded by iceberg scouring into moulded megascale glacial lineations which are recognised morphologically using 3D seismic datasets, and inferred to be comprised largely of glacial till. Otherwise, the sediments are generally described as pebbly sands and considered to be glacimarine in character, deposited during the late Weichselian glaciation (Stoker and Long, 1987; Sejrup et al., 1994).

North of 55°N and west of 0° lies the Forth Formation (Stoker et al., 1985), which crops out extensively at seabed (Figure 3.3) and is split into four members containing marine, glacimarine and estuarine facies (Stoker et al., 1985). In the Devil’s Hole area (see Figure 3.1) it can be seen filling tunnel valleys to depths of 150 m and is Late Weichselian (MIS 2) to Holocene in age (Sejrup, 1994; Graham, 2007).

Radiocarbon dates for the above formations are generally restricted to those obtained in the upper part of the sequence recording the Late Weichselian period and limited Holocene deposition (Stoker and Long, 1984; Sejrup et al, 1987; 1994; King, 1991).

3.2.2 A New Seismostratigraphic Framework for the North Sea

Difficulty in reconciling the older formations described above to more recent work based on 3D seismic data, led Graham (2007) to define a new simplified stratigraphy based on seismic facies and relationships for the study of the glacial sequences of the central North Sea.
The new framework divides the Quaternary succession of the central North Sea into four units based on new observations from 3D seismic reflection datasets and combines it with the BGS framework outline above. The utilisation of the 3D datasets allows the division of stratigraphic units based not only similarities in seismic character in profile, but also by the identification of distinctive morphologies in horizontal timeslice (see Chapter 4 for further details on using 3D seismic data to image buried landscapes in plan form). The buried tunnel valleys which are the focus of this work are one of the significant morphologies imaged in the 3D seismic data and were used to construct the simplified seismic stratigraphy of Graham (2007). The results of this work (Chapters 5, 6, 7 and 8) uses the framework constructed by Graham (2007) to place the buried tunnel valleys in the seismostratigraphic context of the North Sea.

Figure 3.5 provides an example of the seismic stratigraphy from Graham (2007, p. 110) where the base of the tunnel valley (in light blue) provides the division between Units I and II, which are of the most interest to this study. Figure 3.6 provides more detail on the division of the four units by morphological and seismic facies as defined by Graham and described briefly below (2007, p. 111).

3.2.2.3 Unit I

Unit I is identified by Graham (2007) and in this work by its distinctive continuous parallel reflections, which dip slightly towards the centre of the basin (eastwards) within the 3D seismic datasets. In horizontal timeslice, the unit appears largely featureless, but is seen to contain distinctive linear morphologies in a number of locations, interpreted by Graham (2007) and Graham et al. (2007) as iceberg ploughmarks which provide some evidence for cold conditions proximal to the North Sea preceding the incision of the tunnel valleys which define the top of the unit. Figure 3.7a shows an example of Units I and II in vertical cross-profile within Dataset F of this work (see Chapter 4.1 for location), where Unit II comprises the fill of a tunnel valley within the dataset, seen incising into Unit I. Figure 3.7b shows the same location in horizontal timeslice, where Unit I appears relatively featureless, and the outline of the tunnel valley which contains Unit II as its fill is apparent.
Unit I is correlated by Graham (2007) with the Aberdeen Ground Formation of the BGS stratigraphy originally defined by Stoker et al. (1985).

3.2.2.4 Unit II

Unit II is identified within the seismostratigraphic framework of Graham (2007) as filling, and in places, overlying, the buried tunnel valleys which define the top of Unit I. Seismically, Unit II is characterised by its highly variable nature, ranging from chaotic and transparent packages (generally at the base of the unit) to more continuous bedded reflectors (towards the top of the unit). This variability reflects the complexity of fill observed in this and other recent works on tunnel valleys utilising 3D seismic reflection datasets (Lonergan et al., 2006; Kristensen et al., 2007). Unit II is broadly correlated by Graham (2007) to the Ling Bank and Fisher formations of the BGS stratigraphy above, and may also correspond to parts of the Coal Pit Formation. Chapter 7 of this work presents the results of further investigation into the fill of the buried tunnel valleys which define Unit II.

3.2.2.5 Units III and IV

Unit III overlies Unit II, and its base is defined in vertical profile by the high-amplitude, continuous reflection as seen in Figure 3.6a. It is characterised in timeslice by the presence of distinctive ridge and groove linear morphologies, which are interpreted by Graham (2007) and Graham et al. (2007) as buried mega-scale glacial lineations (MSGLs). Unit IV is separated from Unit III, which it overlies, by a change in morphology observed in horizontal timeslice from long, straight MSGLs to shorter, curvi-linear features interpreted as iceberg ploughmarks. When these features are not present, however, the transition between Units III and IV is not always clear (e.g. in Figure 3.6a). Unit III is correlated to the Coal Pit and Swatchway formations in the BGS stratigraphy by Graham (2007). The top of Unit IV is identified as the seabed reflector by Graham (2007) and as such is correlated with the Witch Ground Formation and Forth Formation in the BGS stratigraphy of the central North Sea, into which the seabed tunnel valleys discussed in Chapter 8 incise.
3.3 Chronology of the central North Sea Glacial Record

Absolute chronological control on the glacial sediments and features of the central North Sea has yet to be established. However, combining recent works with the stratigraphy established by the BGS and by Graham (2007) leads to an increased understanding of the timing of the glaciations of the central North Sea, and allows the tunnel valleys studied in this work to be placed into a relative stratigraphical framework.

3.3.1 Pre-tunnel valley incision: Unit I

Unit I of the stratigraphic framework defined by Graham (2007), and identified as the Aberdeen Ground Formation in the BGS stratigraphy, is defined at its top by the regional network of tunnel valleys studied in this work, traditionally associated with the onset of North Sea glaciation during the Elsterian glaciation (ca. 430 ka, MIS 12 – 10). However, the work of Lonergan et al. (2006) has identified that the tunnel valleys which define this regional erosion surface are in fact formed from a number of cross-cutting generations, most likely associated with more than one glaciation.

The base of Unit I is less well-defined, but a number of palaeomagnetic markers, including the Bruhnes-Matuyama reversal (at 780 ka, MIS 19) and the Jaramillo event (1.07 Ma – 990 ka) are present within the unit, constraining the sediments above these events to a maximum of 1.07 Ma in age (Funnell, 1995, Figure 3.2). The Bruhnes-Matuyama reversal in particular can be correlated between seven boreholes within the central North Sea, and into the southern North Sea (Stoker et al., 1983, 1985; Cameron et al., 1987; Balson and Jeffery, 1991). Buried tunnel valleys which define the top of Unit I, and which are the subject of this work, are seen to incise from above this stratigraphic horizon as in Figure 3.8.

A number of previous works, mostly based on micropalaeontological data recovered from cores, find evidence within the sedimentary record of the central North Sea for a glacial event (usually termed the Cromerian Complex) within Unit I between MIS 18 and 12; that is, before the incision of the tunnel valleys which define the top of Unit I, but after the Bruhnes-Matuyama reversal (Stoker et al., 1983; Stoker et al., 1985; Stoker and Bent, 1985; Cameron et al., 1987; Sejrup et al., 1987; Long et al., 1988, see Figure 3.2). Graham (2007) presents morphological evidence in the form of buried iceberg
ploughmarks imaged in 3D seismic datasets to support at least two glaciations of the central North Sea before tunnel valley incision, the younger of which is linked to the Don glaciation of mainland Europe at MIS 16 and can be correlated with the evidence for a Cromerian Complex glaciation above. These additional glaciations are important to this work because they emphasise the possibility that multiple episodes of glaciation, resulting in ice cover over the central North Sea, were feasible over a relatively short period of time and are consistent with the temperature proxies indicated by the oxygen isotope record and Marine Isotope Stages (MIS) shown in Figure 3.2.

3.3.2 Unit II – The Buried Tunnel Valleys
The unconformity at the base of the buried tunnel valleys which defines the transition between Unit I (the Aberdeen Ground Formation) and Unit II (the Ling Bank and Fisher formations) is widely considered to be Elsterian in age (MIS 12-10, Figure 3.2) at its oldest and there is little evidence to dispute this given the lack of any absolute dating for the tunnel valley fill. As is apparent from the palaeomagnetic data discussed above, the buried tunnel valleys are at least younger than the Brunhes-Matuyama reversal at MIS 19, which can be traced throughout the study area, and into which they are seen to incise (Stoker et al., 1983, 1985; Funnel, 1995).

An age for the top of Unit II is less certain, however, and the recent work by Lonergan et al. (2006) reveals a complex history for the buried tunnel valleys in part of the study area, where four cross-cutting generations of tunnel valley are resolved. Accordingly, Unit II may be associated with a number of glaciations. The best constraint on the age of the buried tunnel valleys and their fill lies with the dating of the overlying units III and IV, the Swatchway and Witch Ground formations of the BGS stratigraphy, the upper parts of which have been reliably dated by Sejrup et al., (1994) to ~ 22 ka (Late Weichselian) and the deeper parts as early Weichselian (MIS 5d). The buried tunnel valleys which are the focus of this work can thus be considered as having formed between MIS 16 and MIS 5e, coeval with two glaciations in north-west Europe, the Elsterian and Saalian.

Sedimentary evidence for the extent of the Elsterian glaciation in the North Sea is scarce, and is generally based on the presence of the buried tunnel valleys which mark the top of the Aberdeen Ground Formation (Ehlers and Cameron et al., 1987;
Wingfield, 1991; Balson and Jeffrey, 1991; Praeg, 1996, 2003; Hulse and Lykke-Andersen, 2000; Eissmann, 2002). Recent work by Lonergan et al. (2006) in the central North Sea, and by Jørgensen and Sandersen (2006) and Kristensen et al. (2007) in the eastern North Sea and onshore Denmark, show clearly that the observed networks of tunnel valleys used to define the Elsterian in the North Sea are in fact made up of a number of cross-cutting generations, and thus display a more complex formation history than previously assumed. Therefore it is not possible to link their formation simply to the margin of a single-stage Elsterian glaciation, particularly in the case of the tunnel valleys studied by Lonergan et al. (2006) which, like the tunnel valleys in this study, lie some hundreds of kilometres distant from the southern margin of any proposed Elsterian ice sheet (Figure 3.1).

At least two major advances of ice during the Saalian cold stage (MIS 8-6) are well-defined on land (Ehlers, 1990; 2005), but evidence for ice extent in the North Sea are traditionally limited to Saalian tills offshore Denmark and Holland (Laban, 1995, Figure 3.1) and evidence for ice movement from the north in Denmark, northern Germany and the Netherlands (van den Berg and Beets, 1987; Ehlers, 1990, 2005). Carr (2004) suggests these tills in the southern North Sea provide evidence for extensive North Sea ice cover during MIS 6 - 8, possibly in two stages. Beets et al. (2005) uses microfossil evidence and seismic profiles to date two well-defined tills in a borehole north of the Netherlands as older than MIS 6 (which they define as Saalian) but younger than Elsterian in age. Their work suggests the tills were deposited during an additional ice sheet advance in the southern North Sea at MIS 8, thus supporting a multi-stage, extensive, Saalian glaciation.

Evidence for Saalian age sediments within Unit II fills of the buried tunnel valleys (e.g. in the Ling Bank and Fisher formations of the BGS stratigraphy) is generally limited to the dating of interglacial sediments associated with the Holstenian (MIS 9) from borehole analysis. Glacimarine beds in the Ling Bank Formation and the entire overlying Fisher Formation are therefore inferred to be Saalian in age (Stoker et al., 1985, Knudsen and Sejrup, 1993).

With respect to the combined stratigraphic framework of the BGS and Graham (2007), it is concluded that the buried tunnel valleys in the central North Sea were formed
between MIS 16 and MIS 5e, most likely during the Elsterian and Saalian glaciations. Recent work suggests that the incision of the complex networks of tunnel valleys occurred over a significant period of time, and that it is not possible to link a particular set of tunnel valleys to a single glaciation (Lonergan et al., 2006; Jørgensen and Sandersen, 2006; Kristensen et al., 2007). Furthermore, the new evidence for a multi-stage Saalian glaciation (Beets et al., 2005) emphasises the possibility that the mid to late Pleistocene glaciations were characterised by multiple episodes of ice advance and retreat, which may be related to the cross-cutting generations observed in the work of Lonergan et al. (2006) and Kristensen et al. (2007), and to the multiple generations of tunnel valleys observed in this study, the results of which are detailed in Chapter 5.

3.3.3 Seabed tunnel valleys
A number of tunnel valleys with seabed expression are imaged within the 3D seismic reflection datasets used in this study, and further investigated using the Olex bathymetric dataset as presented in Chapter 8. Their incision from seabed into Early Weichselian sediments (Sejrup et al., 1994; Graham 2007; Bradwell et al., 2008) places their formation during the Last Glacial Maximum of the Late Weichselian (MIS 4 – MIS 2).

3.4 Summary
The rest of this work uses a suite of overlapping 3D seismic reflection datasets to further investigate the extensive networks of buried and seabed tunnel valleys initially related to the Mid to Late Pleistocene glaciation of the central North Sea in the BGS stratigraphy above. Chapter 4 outlines the methods used in the investigation, while Chapters 5, 6, 7 and 8 present the results of this work, as placed in the context of the stratigraphic framework summarised below.

- The sedimentary record of the Quaternary history of the central North Sea is dominated in its upper half by glacigenic sediments related to the Pleistocene glaciations of northwest Europe.
- The new stratigraphic framework by Graham (2007) is used as the basis for the work in this thesis. It is considered to be more suitable for the research presented in this work using 3D seismic reflection datasets, and is based on
seismostratigraphic units defined by reflection characteristics (e.g. reflection continuity, amplitude and morphology) and the presence of unconformities.

- Units I and II in the stratigraphy of Graham (2007) are separated by the presence of a regional network of buried tunnel valleys which are the focus of chapters 5, 6 and 7 of this study.

- In previous studies the buried tunnel valleys within the central North Sea were correlated with the three Pleistocene glaciations recognised in the surrounding onshore regions. However the revised seismostratigraphic framework recognises that the buried tunnel valleys are composed of more numerous cross-cutting generations (Lonergan et al., 2006; Chapter 5 of this work) and are therefore unlikely to be simply related to the three recognised glaciations.

- Instead, the ages of the buried tunnel valleys are constrained by the presence of the Brunhes-Matuyama reversal (at MIS 19), which occurs consistently at a lower stratigraphic horizon than the tunnel valleys, and by the overlying Units III and IV which are consistently identified as Weichselian (MIS 5d – 2) in age by Graham (2007).

- The buried tunnel valleys are therefore associated with the Elsterian (MIS 12-10) and Saalian (MIS 8-6) glaciations of north-west Europe, the latter of which, at least, is likely to have been characterised by multiple phases of ice advance and retreat, which is of consequence to the separation of the observed buried tunnel valleys into cross-cutting generations in Chapter 5 of this work.

- Seabed tunnel valleys present in the study area are investigated further using the Olex bathymetric dataset in Chapter 8, and are identified as younger than the buried tunnel valleys. These seabed valleys are associated with the Last Glacial Maximum (MIS 4 – 2).
Figure 3.1 Location of study area (light blue) in the central North Sea. Extent of the Elsterian (orange), Saalian (green) and Weichselian (blue) Pleistocene glaciations from Ehlers and Gibbard (2004). The dashed line indicates the proposed extent of the Weichselian ice sheet over the southern North Sea by Sejrup et al. (2000, 2005). The northern extent of the Weichselian glaciation (in blue) is at shelf break and the older glaciations are considered to have had the same extent. The Quaternary sediments into which the study tunnel valleys incise are up to 600 m thick towards the centre of the basin (Caston, 1977; Gatilff et al, 1994).
Figure 3.2 Paleomagnetic history and global oxygen isotope record from 1.4 Ma B.P. to the present correlated to the marine isotope stages (MIS) and the north-west European glacial/interglacial stages referred to in the text from Funnell (1995). The B-M boundary marks the switch between the Bruhnes normal chron (in black) and the Matuyama chron (white) at 780 ka B.P.
Figure 3.3a) Fence diagram redrawn from Gatiliff et al. (1994) showing relationships between the nine Quaternary formations identified by Stoker et al. (1985) and used as the basis for the stratigraphic framework in the central North Sea until recently. Tunnel valleys are apparent as significant erosional features, incising from three levels. For location of panels at seabed see Figure 3.3b.

Figure 3.3b Quaternary seabed sediment map from Gatiliff et al. (1994) showing the surface distribution of Quaternary formations in the central North Sea based on the BGS Quaternary Geology sheet. Black lines and letters show locations of the 2D seismic profiles which form the basis for the fence diagram in Figure 3.3a. Note the change in nomenclature to the south east as the diagram merges with the “southern North Sea” seabed map sheet east of 0° and south of 56°N.
Figure 3.4 BGS Chronostratigraphy for the central North Sea modified from Gatliff et al., (1994). Additional MIS and dates from Scourse et al. (2002), Sejrup et al. (2005) and Maher and Hallam (2005).
Figure 3.5 Simplified seismic stratigraphy made up of four units for the central North Sea as constructed by Graham (2007) using 3D seismic reflection datasets. The light blue line indicates the base of Unit II, identified as the base of the regional set of buried tunnel valleys which are the focus of this work. The units are discussed in more detail in Chapter 3.2.2 of the text.
<table>
<thead>
<tr>
<th>Revised unit</th>
<th>Data</th>
<th>Acoustic character</th>
<th>3D timeslice character</th>
<th>Plan-view morphology</th>
<th>Unit thickness</th>
<th>No. of loops (if bedded)</th>
<th>Depth in seismic volume</th>
<th>Previous interpretations</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNIT IV</td>
<td>3D</td>
<td>Moderate amplitude with undulating, irregular base, sometimes thick reflections (due to separable resolution of 3D data). Flat-lying.</td>
<td>Cross-cutting, curvilinear features</td>
<td>&lt; 20 metres</td>
<td>1-2</td>
<td>multiple (&gt;10)</td>
<td>0-20 metres</td>
<td>Iceberg scoured base (Stoker and Long, 1984; Long and Praeg, 1997)</td>
</tr>
<tr>
<td></td>
<td>2D</td>
<td>Flat-lying, bedded and laminated. Minorly undulating with an irregular erosional base. Bedding reflects 'draping' over underlying surface.</td>
<td>Parallel lineations</td>
<td>&lt; 65</td>
<td></td>
<td></td>
<td></td>
<td>None morphologically. Subglacial to proximal glaciomarine facies (Sejrup et al., 1987; 1994; Carr et al., 2006)</td>
</tr>
<tr>
<td>UNIT III</td>
<td>3D</td>
<td>Bedded to chaotic/ transparent acoustic package. Where bedded, highly irregular flat-lying horizons. Smoother base, irregular top.</td>
<td>Tunnel valley fill, intra-formation channels.</td>
<td>absent to &gt;100 m?</td>
<td></td>
<td></td>
<td></td>
<td>Tunnel valleying (e.g. Jansen et al., 1976; Fyfe, 1983; Wingfield, 1990; Ehlers and Wingfield, 1991; Praeg, 1996; 2003; Lonergan et al., 2006)</td>
</tr>
<tr>
<td></td>
<td>2D</td>
<td>Structureless to chaotic sequence. Upper and lowerboundaries well defined, irregular internal reflections discontinuous and indistinct.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UNIT II</td>
<td>3D</td>
<td>Variable. Channel features at multiple horizons with structureless 'blanketing' subunits, some high amplitude packages and chaotic/transparent units within channels. High amplitude zones around channel edges. Base of unit major unconformity.</td>
<td>Incised by valleys</td>
<td>&gt;100 m</td>
<td>multiple</td>
<td></td>
<td>&gt;100 m</td>
<td>Deltaic to prodeltaic, non-glacial deposits (Stoker and Bent, 1988). Isolated glaciomarine horizons (Stoker and Bent, 1985).</td>
</tr>
<tr>
<td></td>
<td>2D</td>
<td>Highly variable. Chaotic to laminated with multiple internal boundaries and unconformities, incising from different depths. Discordant reflectors and gas blanking common.</td>
<td>Discrete horizons with straight to curvilinear lineations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UNIT I</td>
<td>3D</td>
<td>Horizontally bedded with localised chaotic layers. Irregular erosion surface as upper boundary. Inverse truncates internal reflectors. Amplitude variations, particularly around magnetic excursions. As above, but with clear truncation of beds by channels. Internally stronger reflections. Lower part of unit often masked by multiples and reduced S/N ratio. Distinct internal facies.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2D</td>
<td>Horizontally bedded with localised chaotic layers. Irregular erosion surface as upper boundary. Inverse truncates internal reflectors. Amplitude variations, particularly around magnetic excursions. As above, but with clear truncation of beds by channels. Internally stronger reflections. Lower part of unit often masked by multiples and reduced S/N ratio. Distinct internal facies.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Figure 3.6 Four unit stratigraphy for the Witch Ground basin Quaternary from Graham (2007, p.111)
Figure 3.7 (a) Vertical profile within the representative 3D seismic survey, Dataset F (see Figure 4.2 for location) showing the separation of the sedimentary sequence into four seismic units as defined by Graham (2007). Units I and II are separated by the base of the tunnel valley (solid white line) which is representative of the regional network in the study area. The top of Unit II is shown by the dashed white line, which is overlain by Units III and IV. The latter two units are not distinguishable in this locale. (b) Horizontal timeslice at 336 ms TWTT (two way travel time) in Dataset F showing the location of the profile a-b in Figure 3.6a. Note the relatively featureless nature of Unit I in timeslice.
Figure 3.8 Time-surface map of the Bruhnes Matuyama magnetic reversal at 0.78Ma interpreted from the merged 3D seismic datasets utilised in this work. Figure 4.5b Profile along line A-A' within the dataset cnsmerge (see Figure 4.2) showing the Bruhnes-Matuyama magnetic reversal horizon as interpreted in yellow. Tunnel valleys in cross-section are seen between 300 and 350 ms TWTT towards the west of the profile.
Chapter 4: Methodology

4.1 Seismic Datasets

Buried tunnel valleys in the central North Sea area were investigated in this work using a number of overlapping three-dimensional (3D) seismic reflection datasets. Section 4.1.1 outlines the geophysical basis of seismic reflection theory, the use of 3D seismic datasets, and their suitability for identifying and analysing glacigenic features in the study area. Section 4.1.2 provides more detailed information on the datasets themselves and Section 4.1.3 discusses the uncertainties associated with the use of seismic reflection data.

4.1.1 Seismic Reflection Theory

Seismic reflection data can provide information on the geometry and physical properties of otherwise inaccessible geologic structure; seismic reflections are generated as a result of a contrast in acoustic impedance (velocity of material x density of material) between strata and measured as a function of two way travel time (TWTT) (Davies and Austin, 1997; Stoker et al., 1997; Brown, 1999).

Seismic reflection methods involve the transmission and reception of acoustic waves of a dominant frequency to an offset receiver. Successive reflections are recorded as traces (adjusted reflected waves) and built up into seismic profiles, or volumes, as in the case of multi-channel 3D seismic surveys. Detailed acquisition and processing methods for 3D surveys are discussed further by Yilmaz (2000), and Bacon et al. (2003).

Resolving geological features is the primary aim of the 3D seismic reflection method and resolution, both horizontally and laterally, is a function of seismic wavelength, \( \lambda \) (Brown, 1999). Wavelength in turn is related to frequency (f) and material velocity (v) as below:

\[
v = \lambda \cdot f
\]

The velocity of sound in solids will increase with depth (i.e. acoustic impedance decreases) as strata become more compacted. Dominant frequencies will also decrease with depth as higher frequencies are attenuated. Seismic wavelength will therefore increase with depth, lowering the limits of resolution as shown in Figure 4.1a.
Consequently, seismic surveys are configured to produce the best resolution for the target depth. The commercial 3D seismic reflection surveys used in this work, as shot for the oil and gas industry, are generally concerned with depths of 2 – 6 km beneath the surface; hence they tend towards low frequency configurations of ca. 5 - 80 Hz. Offshore research-led seismic reflection surveys configured specifically to investigate seabed and shallow geological features may have frequencies up to kHz range and correspondingly high resolution capabilities, with vertical resolution up to 10 cm in 2D (King et al., 1996; Novak and Stoker, 2001; Kluiving et al., 2003; Evans et al., 2004; Nordfjord et al., 2004) and occasionally 3D (Davies and Austin, 1997; Muller et al., 2002).


Vertical resolution for seismic reflection data is expressed as a function of dominant source wavelength (λ) and is generally accepted to be ¼ λ for the limit of separability – the ability to resolve the top and base of a sedimentary layer. (Brown, 1999; Yilmaz, 2001; Praeg, 2003; Bulat, 2005). Commercial source frequencies in this study range between 5 and 80Hz, providing maximum vertical resolution of approximately 8m in the shallow section (< 1s TWTT) where sediment velocity is estimated to be ca. 1700 - 1800 ms⁻¹ as in Praeg (1996, 1997, 2003), Lonergan et al. (2006) and Graham (2007). For the interpretation of glacigenic geomorphological features such as tunnel valleys and mega-scale glacial lineations (MSGIs) this vertical resolution is more than adequate.
The main advantage of 3D seismic reflection imaging in the interpretation of geomorphological features is its capacity for viewing in the horizontal plane (timeslice), with associated high lateral resolution even at low frequencies. This is a result of two factors: improved lateral resolution due to 3D seismic processing techniques and close survey spacing, and the ability of 3D data to accurately represent lateral geomorphological form (Brown 1999).

For 3D seismic reflection data, lateral resolution is discussed as a function of the size of the Fresnel Zone, which indicates the radius of a spherical wavefront interacting with a flat reflector and is described by the equation below where \( F \) is Fresnel radius, \( V \) is velocity of the substrate, \( T \) is two way travel time to reflector and \( f \) is dominant frequency (Brown, 1999; Yilmaz, 2001; Bulat, 2005).

\[
F = \frac{V}{2} \sqrt{\frac{T}{f}}
\]

Migration processing of 3D seismic reflection data collapses the Fresnel zone to \( \frac{1}{4} \lambda \) (for further discussion see Bulat, 2005, p.36-37) but practical considerations mean a value of about half the dominant wavelength is commonly accepted (Brown, 1999; Yilmaz, 2001; Bulat, 2005). However, working measurements of lateral resolution are by and large dependant on the spatial sampling of the 3D seismic survey, as this measure is often coarser than primary wavelength (Bulat, 2005; Cartwright and Huuse, 2005). For this study, lateral resolution therefore ranges from 12.5 m to 100 m depending on dataset, as summarised in Table 4.1.

The nature of 3D seismic reflection volumes allows them to be explored both vertically (in cross section) or horizontally (in timeslice), as in Figure 4.1b. The ability to image in the horizontal plane makes them ideal for examining laterally complex but relatively shallow features such as channels, which have only subtle expression in cross section. As well as comparing favourably to 2D surveys for capturing the ‘true’ geomorphology of such features, the use of timeslices for interpretation can also be seen within 3D volumes themselves, as shown in Figure 4.1c where a tunnel valley within the cnsmerge dataset (ca. 100 m horizontal resolution) is clearly imaged in timeslice, but is
undetectable in vertical cross section, due to problems with merged data, seabed noise and velocity pull-ups (discussed further in Chapter 4.1.3).

Although caution must be taken to avoid simplifying the relationship between TWTT and depth, if subsurface strata are relatively flat lying and have fairly consistent velocities, as in the study area of the central North Sea, timeslice images from 3D seismic reflection data may be interpreted as directly analogous to palaeosurfaces, allowing geomorphological features to be analysed directly. As Brown (1991, p.91) puts it: “the study of horizontal sections and horizon slices can provide a bird’s-eye view of ancient stratigraphy, analogous to the view of modern stratigraphy obtained out of an aeroplane window”.

4.1.2 Seismic Stratigraphy.

To infer geological information from 3D seismic reflection datasets, a consistent approach must be followed and assumptions made about the nature of reflections and their analogy to stratal surfaces. This work applies the concepts of seismic stratigraphy to identify and analyse the geomorphology and fill of buried tunnel valleys in the central North Sea using 3D seismic datasets. A key point in seismic stratigraphy is that most abrupt contrasts in acoustic impedance, which generate seismic reflections, will occur at lithological breaks along major bedding surfaces (e.g. Vail et al., 1977). Based on this assumption, reflection terminations (truncation, onlap, etc.) are interpreted to mimic stratal relationships like erosion and fill. Such terminations can be used to identify unconformities (e.g. at the base of tunnel valley networks), which define units (“packages”) of strata. Within the context of these stratal units, seismic facies can be identified using the descriptive attributes of reflections (continuity, spacing/frequency, amplitude, geometry), and then interpreted in terms of analogous rock facies (e.g. lithologies, textures, bedding geometries, sedimentary structures at a scale appropriate to seismic resolution).

4.1.3 Study Datasets.

Fourteen overlapping 3D seismic reflection datasets were used to map complex networks of buried Pleistocene tunnel valleys in the central North Sea. Survey areas vary in size from 8 x 12 km to 60 x 100 km and accompany a large, merged, 3D dataset, termed cnsmerge (CNS Megasurvey, PGS Ltd, bin size 100 m) to provide
comprehensive coverage of the British sector of the central North Sea. Appendix A in this thesis details the acquisition and processing of the merged dataset in more detail. Figure 4.2a displays the location of Datasets A to M referred to in this work in the context of the central North Sea. Figure 4.2b presents the configurations of the overlapping datasets A to J in the northern half of the study area in more detail. Table 4.1 lists the dimensions and bin spacing for the datasets used in this study.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Survey Area (approx. km$^2$)</th>
<th>Bin size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>700</td>
<td>25 x 25</td>
</tr>
<tr>
<td>B</td>
<td>830</td>
<td>25 x 25</td>
</tr>
<tr>
<td>C</td>
<td>700</td>
<td>25 x 25</td>
</tr>
<tr>
<td>D</td>
<td>960</td>
<td>25 x 25</td>
</tr>
<tr>
<td>E</td>
<td>1352</td>
<td>25 x 25</td>
</tr>
<tr>
<td>F</td>
<td>1200</td>
<td>25 x 25</td>
</tr>
<tr>
<td>G</td>
<td>460</td>
<td>12 x 25</td>
</tr>
<tr>
<td>H</td>
<td>3750</td>
<td>50 x 50</td>
</tr>
<tr>
<td>I</td>
<td>3750</td>
<td>50 x 50</td>
</tr>
<tr>
<td>J</td>
<td>3750</td>
<td>50 x 50</td>
</tr>
<tr>
<td>K</td>
<td>3750</td>
<td>50 x 50</td>
</tr>
<tr>
<td>L</td>
<td>3750</td>
<td>50 x 50</td>
</tr>
<tr>
<td>M</td>
<td>1000</td>
<td>12.5 x 12.5</td>
</tr>
<tr>
<td>cnsmerge</td>
<td>60 000</td>
<td>100 x 100</td>
</tr>
</tbody>
</table>

*Table 4.1 Area and bin size of the 14 3D seismic reflection datasets used in this study (for location see Figure 4.2).*

Although originally configured for the exploration of commercial hydrocarbon reservoirs at depths of more than 1 km beneath sea bed, the reflection datasets provide good quality imaging of shallower Quaternary sections. Dense networks of tunnel valleys are found within the top 600 ms two way travel time (TWTT). Depth conversions were based on typical Quaternary North Sea sediment velocities between 1600ms$^{-1}$ and 1800ms$^{-1}$ as used by Praeg (1996, 1997, 2003), Huuse and Lykke-Andersen (2000), Lonergan et al. (2006) and Graham (2007).

Figure 4.3 presents selected tunnel valley margins as a result of mapping all resolvable tunnel valleys in all datasets across the study area. Variation in tunnel valley density is a largely a result of the concentration of high quality datasets to the north of the study area, and in the Dataset M area to the south (see Figure 4.2 for location; Chapter 6.3 for more on differences in tunnel valley frequency in the study area). The use of several
overlapping datasets provided a number of advantages when mapping the complex networks of tunnel valleys. Firstly, systematic identification of tunnel valleys was possible at a regional scale using the merged dataset, cnsmerge, with 100m bin size. This coarse exploration framework provided direction for further, more detailed work, and reduced bias towards the areas of greatest dataset density in the north of the study area. Secondly, it was possible to trace and map tunnel valleys across multiple datasets independently, reducing interpretation error and constraining tunnel valley geomorphologies to a high degree of accuracy. Finally, exploiting areas of overlapping coverage reduced uncertainty associated with poor signal to noise ratios in some datasets. By re-mapping areas containing anomalies such as disruptive seabed multiples, shallow gas, and acquisition footprints in different volumes, it was often possible to minimise their impact on tunnel valley mapping as described by Bulat and Long (2001), Long et al. (2004), and Bulat (2005) for seabed features. However, at a regional scale, some instances of generally poor quality data remain in the merged dataset (cnsmerge), and their boundaries are included in Figure 4.3.

Figures 4.4a and 4.4b provide time-depth information for the tunnel valleys mapped in this work which shows the majority of tunnel valleys margins were recorded between 100 and 300 ms TWTT, equivalent to less than 170 m beneath seabed. Tunnel valley depth decreases towards the south of the study area, where most occur less than 90 m beneath seabed.

4.1.4 Uncertainty and Errors

Although the 3D seismic datasets used in this survey are able to provide high quality imaging for the interpretation and mapping of buried tunnel valleys, it must be acknowledged that the reflection datasets are time-images and may be affected by problems with signal to noise ratio and processing errors. For this study, problematic issues included the presence of acquisition footprints, velocity pull-ups, low signal to noise ratios at seabed and seabed multiples within the datasets. Merged datasets also presented problems when data quality changed abruptly across dataset boundaries, and shallow gas caused difficulties in some interpretation. However, interpretation within multiple datasets and maximum utilisation of their 3D nature allowed most of these problems to be overcome.
Survey acquisition ‘footprints’ occur within the majority of 3D seismic reflection surveys as systematic noise imaged in the direction of acquisition (Bulat, 2005). Acquisition footprints are present within all the datasets in this study, to varying degrees of severity as shown in Figure 4.5a-c. Timeslices can still be used to image tunnel valleys even in the worst cases (i.e. Figure 4.5c) and tunnel valleys poorly imaged within one dataset were traced within another if possible at a similar TWTT. Figure 4.5b displays an example from Dataset H (see Figure 4.2 for location) where an approximately e-w trending acquisition footprint can be seen worsening towards the north of the dataset, indicating static shifts between merged surveys.

Static shifts are related to minor differences in the acquisition parameters and processing between adjacent surveys, which may later be merged or composited (Long and Bulat, 2001; Bulat, 2005). Figure 4.5b and 4.6a show the effect of this data artefact within Datasets H and I (see Figure 4.2 for location) respectively. Generally, time shifts were in the order of less than 12ms TWTT, and timeslice images were of sufficient quality to trace tunnel valleys between datasets of varying quality, as is apparent from Figure 4.6a. In the worst cases, the reduced quality of tunnel valley interpretation was noted for the recorded horizon, and care was taken not to use the margins for detailed geomorphological study.

Poor signal to noise ratios in the top 0 – 150 ms TWTT beneath seabed of commercial 3D seismic data has been noted by Huuse and Lykke-Andersen (2001), Bulat (2005), and Graham (2007) and are generally due to the considerable difference in acoustic impedance between water and sediment at seafloor which encourages significant refraction. In shallow water, the configuration of the acoustic source for km-scale depths will also decrease the quality of reflection from seabed and shallow depths (see Praeg, 2003, p.7 and Bulat, 2005, p.30 for a more detailed discussion). Figure 4.6b displays this phenomenon in cross profile within the Datasets L, where the shallow seismic reflection appears corrugated and discontinuous. Fortunately, the majority of the buried tunnel valleys of interest to this work incise from at least 200 ms TWTT. Furthermore, as in the case of acquisition and static shift artefacts, timeslices often provide a resolvable margin for datasets affected by this problem, as seen in Figure 4.1c, where the timeslice at 144 ms TWTT clearly images the margins of a tunnel valley.
while the accompanying cross section cannot resolve the feature due to data problems near seabed.

Multiples represent re-reflected signals within a seismic reflection dataset (Stoker et al., 1997). A seabed multiple, where primary waves are reflected back to the seabed and then propagated downwards, produces a replication of the seabed reflector at depth, and is fairly common in shallow marine work using commercial 3D seismic data as noted by Huuse and Lykke-Andersen (2000), Long and Bulat (2001), Praeg (2003), Bulat (2005), and Graham et al. (2007) and may be reduced in 3D seismic processing. Figure 4.6c shows a clear example of a multiple reflector at approximately 300 ms TWTT which follows the seabed reflector in Dataset L. A common problem in interpretation is the possibility of wrongly mapping a tunnel valley base and/or margin as incising from the multiple reflector (at a greater TWTT) as the presence of a tunnel valley above the multiple may causes similar effects (i.e. the abrupt termination of the lateral surface reflection and associated flank slopes) to a multiple as would a tunnel valley truly incising from the higher stratigraphic level.

A final imaging problem associated with the study datasets was the presence of disruptive, bright amplitude variations in timeslice, shown in Figure 4.6d, and most likely the result of shallow gas. This did not tend to affect the digitisation of tunnel valley margins in timeslice, but caused problems in identifying and tracking fill packages, and when using auto tracking routines to create 3D horizons as in Section 4.2.1. Careful calibration of colour schemes and seed points reduced the problems, but the bright spots hindered the interpretation of some cross cutting relationships, and these areas were recorded as un-resolvable.

Velocity pull-ups are another feature associated with the 3D seismic reflection datasets, caused by a change in sediment velocity (and therefore acoustic impedance) between the tunnel valley fill and the strata into which the valleys incise. This can cause problems when interpreting reflectors underlying the tunnel valleys which appear falsely convex upwards; the 'pull-up' effect, seen in Figure 4.6e. Due to a lack of boreholes penetrating the tunnel valleys themselves, it is not possible to accurately correct the effect of the pull-up on the lower stratigraphic levels, however, their fairly rare occurrence within the dataset means their signature in any interpreted horizon is
fairly distinctive and can be accounted for. Velocity pull ups can also be useful as they may imply a coarse/sandy infill for a tunnel valley (i.e. a decrease in acoustic impedance) and so can be utilised in fill interpretation.

4.2 Interpretation and analysis of central North Sea Tunnel Valleys

Individual tunnel valleys were identified and mapped systematically across all 3D seismic reflection datasets shown in Figure 4.2. Detailed investigation of tunnel valley morphology and fill was carried out using a number of interpretation packages as described below in Section 4.2. Geomorphological measurements of width, depth, valley wall steepness, and orientation were made as outlined in Section 4.2.2.

4.2.1 Workflow and Tools

3D seismic data were initially viewed and interpreted as amplitude time slices using Landmark's Seisworks software package in which display options for colour schemes, scaling and horizontal/vertical views were easily manipulated. Tunnel valley base and walls were recognised by truncated discontinuities in otherwise gently dipping reflectors. For each dataset, the approximate location and density of tunnel valleys present was identified in timeslice, generally at around 350ms TWTT. The margins of each tunnel valley were then digitised in horizontal timeslice within the Seisworks package, working from the base upwards at intervals of 4-24ms depending on data quality. Vertical cross profiles were used to verify the position of margins and assist in areas of difficulty. Any data quality issues or problems were recorded in detail and their location marked as discussed in Section 4.2.3. Each tunnel valley was mapped as a separate 'horizon'. By delineating margins in successively deeper timeslices, an accurate recreation of morphology was recorded for more than 180 individual tunnel valleys. Figure 4.7a shows two tunnel valleys (tvk and tvb) clearly visible in timeslice at 308 ms TWTT within Dataset C (see Figure 4.2 for location). Figure 4.7b displays their margins digitised every 8 ms in timeslice for their entire depth, where it becomes apparent that tvk cross-cuts tvb. Figure 4.7c shows the same tunnel valleys viewed in vertical cross profile along line a-a', with their margins highlighted as dashed white lines.

Digitised datapoints comprising the interpreted margins for individual tunnel valleys were then exported in the xyz format (recording Cartesian co-ordinates and depth for
each point) for use in other interpretation packages. Fault3d software developed by Lister (2004) was used to create 3D surfaces for the tunnel valleys. Optimum results were obtained using a ‘Delauney with Steiner points’ triangulation algorithm within Fault3d, (which maximises minimum angles of all triangles in the surface mesh) and a single iteration of surface smoothing. Fault3d surfaces were then imported back into Seisworks to assist with the interpretation of fill and geomorphological measurements and features, and to compare interpolated surfaces created within the Seisworks package itself.

Digitised margins for tunnel valleys were also exported to Landmark’s GeoProbe software package which allows dynamic 3D visualisation and contains powerful tools for analysis of channel fill. Seed points were identified within high amplitude fill packages constrained by individual valley limits within the 3D volumes and propagated using tracking algorithms within the software. Morphological features of the tunnel valleys, such as hanging valleys and interfluves, were also well-imaged within the GeoProbe software.

GIS software (ArcMap 9, ESRI) was used to measure some tunnel valley geometries, georeference datasets at a variety of scales, and incorporate maps and country outlines from other sources.

Figure 4.8a shows a 12 x 24km 3D seismic volume from Dataset B (see Figure 4.2 for location), imaged in GeoProbe, with a number of cross-cutting tunnel valleys outlined at 372 ms TWTT. The margins of the buried tunnel valleys were identified in timeslice where their lateral geomorphology is most striking, and their bases further verified by vertical cross-section as in Figure 4.8b. Figure 4.8c shows the triangulated 3D surface for the tunnel valley tvc in Figure 4.8a created from the above interpretation using the Fault3d software (Lister, 2004).

4.2.2 Tunnel Valley Measurements

Geometrical measurements of tunnel valley geomorphology were carried out systematically across the study area datasets. Estimates for systematic and interpreter error are discussed in turn, although practical values were often dependent on survey sample size and resolution as discussed in Section 4.1.3. Where data quality was an
issue (for example, in Dataset L which contains a strong seabed multiple, Figure 4.6c) this was recorded in the interpretation of the tunnel valley geomorphology.

4.2.2.1 Widths and Lengths

The majority of widths and length measurements for buried tunnel valleys were carried out within the Seisworks interpretation software and based on the digitisation of valley margins as described above. More detailed work was carried out when necessary using the triangulated surfaces for individual tunnel valleys created using Fault3d software (Lister, 2004) and outlined in the previous section.

Widths for all tunnel valleys were averaged from at least six shoulder-to-shoulder measurements \( w_{1-6} \) made perpendicular to valley direction as shown in Figure 4.9a. Maximum and minimum widths were also recorded for each tunnel valley. Lengths were measured along thalweg \( L_t \) and also as a 'straight line length' \( L_s \) from start to finish of each tunnel valley as in Figure 4.9a. Sinuosities were calculated as the ratio between the two measurements \( L_t/L_s \). Errors for both measurements were partially dependant on the horizontal resolution of the individual dataset (see Section 4.1.2) and so vary between 12.5 m and 100 m. Interpreter error was estimated to be \( \pm 12.5 \) m as minimum and was reduced by averaging multiple measurements.

4.2.2.2 Valley Wall Steepness and Asymmetry

Asymmetry measurements were made by comparing the steepness of valley walls perpendicular to thalweg in cross section, usually within the Seisworks software package, and taking care to incorporate vertical exaggeration in the calculations. Valley wall steepness \( \theta \) was measured to the nearest degree from horizontal to the base of the tunnel valleys to a best fit line along the valley wall flank, as in Figure 4.9b. All measurements of valley wall steepness were dependent on sediment velocity values for depth conversion, and calculated for values between \( v =1700 \) ms\(^{-1} \) and \( v =1800 \) ms\(^{-1} \) with resulting values of \( \theta \) having an error of \( \pm 1^\circ \). Although this affects the accuracy of the angle measurements themselves, relative measures of valley wall steepness are consistent within the datasets and useful for comparing the extent of asymmetry. A tunnel valley was generally considered to be asymmetric in cross-profile if the difference in steepness between the two valley walls was greater than \( 5^\circ \).
4.2.2.3 Orientation

Orientations for all the tunnel valleys were measured based on their margins digitised originally in Seisworks as described above in Section 4.2.1. Location and depth (xyz) data for each tunnel valley was then exported to ArcGIS 9.0 (ESRI) in which accurate georeferenced measurements were made of azimuthal direction. In order to take into account the variation in course of individual tunnel valleys, orientations were measured twice: firstly using a number of weighted measurements along (or as near as possible an approximation to) the base of the tunnel valley, and then as a 'straight line orientation' measured from start to end of the tunnel valley. Figure 4.10a shows how the reach of a tunnel valley was divided into lengths with the same orientation in red. For each section, both the angle from 0° - 180° at geographic north, and the length of the stretch was measured to give a weighted value of azimuth (θₗ), usually where 1 unit = 1 km. Each measurement was presented and analysed using θₗ and θₗ + 180° (i.e. axial measurements) as palaeoflow direction is uncertain as in Figure 4.10b. Thus, the weighted measurement incorporates the planform geometry of the tunnel valleys and allows for direct comparison between all tunnel valleys, while the straight line measurement (θₛ) gives an approximate estimate of an average valley orientation.

Rose diagrams (displaying frequency-azimuth) were plotted for the weighted measurements using a spreadsheet provided by Jolly (pers. communication) and for the straight line orientations in the GeOrient software package. Unless specified otherwise, the outer circle of any rose diagrams represents a frequency of 10, and sector angles are 9° (i.e. 40 sectors per circle). Figure 4.10c shows the weighted rose diagram plotted for the tunnel valley measurements in Figure 4.10a which incorporates the central bend and a strong NNE-SSE component not obvious from the straight line orientation.

Circular analyses for tunnel valley orientation measurements were calculated as outlined by Fisher (1993, and references therein) and Mardia and Jupp (2000). Descriptive statistics were based on the calculation for the vector mean created by combining the resultant vector direction for each set of measurements. The vector mean has two properties: mean resultant length (r) and mean direction (θ). Circular Variance (V) is calculated simply as 1-r with results near to 0 implying a high value for r and therefore more cluster around the mean and a higher directionality (Fisher, 1993, p.32; Mardia
and Jupp, 2000, p.18). As palaeoflow direction is unknown all orientation data are assumed to be axial. The circular standard deviation (v) is calculated in a similar fashion to that for linear data and gives an idea of the dispersion of the data from the average value (Fisher, 1993, p.19). A standard error for orientation measurements was also calculated from the Mean Resultant Length (r) and 95% and 99% confidence levels were derived from Fisher (1993, p.76). Orientations measured for the tunnel valley shown in Figure 4.10b shows a mean direction of 170 and a mean length of 0.63 compared to a straight line orientation of 157. Orientation measurements are also described with an interpreter error estimated at approximately ±1° and minimised by multiple measurements.

A number of tests can be used to evaluate whether orientation measurements are distributed uniformly (i.e. display no preferred orientation), the simplest of which is Rayleigh's Uniformity Test which evaluates for a null hypothesis where the data are distributed uniformly (Fisher, 1993; Mardia and Jupp, 2000, p. 94). The Watson-Williams F-test was used to test whether different sets of orientation measurements from groups of tunnel valleys displayed significantly different preferred orientations (Fisher, 1993, p.126; Mardia and Jupp, 2000, p. 129). All tests assumed that orientation data were drawn from a population within the von Mises distribution, roughly equivalent to the normal distribution in linear data (a unimodal distribution scattered around a central value), and shown to be the case in Chapter 6.

4.2.2.4 Depths and Longitudinal Profile

The majority of vertical tunnel valley measurements were recorded as milliseconds TWTT (two way travel time), as lack of borehole data from within tunnel valley sediments themselves hampered accurate knowledge of sediment velocity. Depth conversion would therefore lack sufficient details of lateral and vertical changes in fill to be fully relevant. Estimated depths and thicknesses were calculated using sediment velocities of between 1700 ms\(^{-1}\) and 1800 ms\(^{-1}\), in common with similar work using 3D seismic datasets in the North Sea (Praeg, 1996; Lonergan et al., 2006; Graham, 2007). Absolute depth measures are therefore subject to variations of at least ±3% as a result of the variation in sediment velocity used and are presented as approximations, although they are consistent within datasets. Interpreter error was dependant on vertical resolution and sampling rate, generally between ±4 and ±12 ms TWTT, but again
consistent within datasets. Overall, a depth converted TWTT measurement used to create a longitudinal profile was associated with a maximum error of ± 11 m related to the difference in maximum (1800 m/s) and minimum (1700 m/s) sediment velocities, and a maximum interpretation error of ± 12 ms TWTT.

Longitudinal profiles were obtained from 3D interpolated surfaces built for individual tunnel valleys in the GeoProbe and Fault3d software packages and corroborated directly with the 3D seismic datasets as observed in Seisworks. TWTT was measured along the base of a number of tunnel valleys with spacing of measurements dependant on the resolution of the dataset and resultant quality of 3D surface.

4.3 Summary

- 14 overlapping 3D seismic reflection datasets are used within this study to investigate buried and surface tunnel valleys in the central North Sea.
- The nature of the 3D seismic reflection data allows the tunnel valleys to be imaged both in plan-view and in profile, providing an excellent basis for the analysis of tunnel valley morphology and fill over an extensive study area.
- Some uncertainties and errors are associated with the use of 3D seismic reflection datasets, and these issues are considered and recorded during interpretation.
- The buried tunnel valleys in the study area were investigated systematically using a number of techniques and software packages to record fill, widths, depths, orientation, and steepness.
Chapter 4 - Figures

Figure 4.1a Diagram illustrating the relationship between velocity, frequency, wavelength and depth as applicable to seismic reflection data (Brown 1999).

Figure 4.1b Schematic illustration of terms used to describe 3D seismic reflection data.

Figure 4.1c Comparison of tunnel valley from the dataset cnsmerge imaged in timeslice (left) and in profile along the line a-a’ (right). The tunnel valley is clearly visible in timeslice, but unresolvable in profile, highlighting the advantages of the 3D seismic reflection datasets.
Figure 4.2 (a) Location map of study area showing 3D seismic datasets used in this study, labelled A - M and also including the regional dataset cnsmerge. (b) Detailed location map of Datasets A - K in the northern part of the study area.
Figure 4.3 Result of initial reconnaissance mapping of all buried tunnel valleys in the study area showing increased density relating to the location of the 3D seismic reflection datasets A to M located in Figure 4.2. The remainder of the tunnel valleys are imaged in the cnsmmerge dataset.
Figure 4.4a Map of all tunnel valleys recorded within the study area where colour illustrates the two way travel time (TWTT) of best recorded outline for each tunnel valley. Tunnel valleys occur closer to sea bed towards the south and east of the study area as shown in Figure 4.4b where the colour scale displays only tunnel valleys between 0 and 200 ms TWTT (< 175m beneath sea bed).
Figure 4.5 (a-c) Worsening acquisition footprints observed in timeslice in (a) Dataset B (b) Dataset H (c) Dataset D (see Figure 4.2 for location).
Figure 4.6 (a-e) Examples of data and imaging problems within the 3D seismic reflection dataset used in this study. See text for more details.
Figure 4.7 (a-c) Interpreting tunnel valleys in 3D seismic reflection data in Dataset C where (a) shows two cross-cutting tunnel valleys in timeslice at 308 ms TWTT (b) shows the tunnel valley margins digitised and (c) shows the two valleys in cross profile with their margins as white dashed lines.
Figure 4.8 (a-c) Tunnel valleys from Dataset B imaged in Geoprobe (a) and Seisworks (b) and (c) a surface created for tvc in the software package Fault3d.
Figure 4.9 a) Example of measuring widths (in red) and lengths (blue) for an individual tunnel valley in Dataset F. b) Measuring valley wall steepness and asymmetry for a tunnel valley (base in yellow) in Dataset F.
Figure 4.10 (a-c) Example of the measurement of weighted and straight line orientations for an individual tunnel valley. See text for further explanation.
Chapter 5: Results — Generations of Buried Tunnel Valleys

5.1 Concept and Overview

The extent and quality of the 3D seismic datasets used in this work allows the scale and complexity of the buried tunnel valleys in the central North Sea to be fully realised. Figure 5.1a shows a typical timeslice through a 3D seismic dataset from the northern half of the study area which displays a strikingly dense network of tunnel valleys. Figure 5.1b illustrates the complexity of the buried tunnel valleys in seismic cross-section. However, the quality of much of the data also allows the apparently complex networks to be separated into discrete generations, mainly by their cross-cutting relationships. These generations can be extrapolated to a number of scales, from individual datasets (ca. 20 x 25 km$^2$) to regional areas (100 x 100 km$^2$), with varying degrees of confidence.

Recent work carried out by Lonergan et al. (2006) and Kristensen et al. (2007) in the North Sea, and by Jørgensen and Sandersen (2006) onshore in Denmark, found evidence for multiple generations of buried tunnel valleys using 3D geophysical methods. Lonergan et al. (2006) described four resolvable generations of tunnel valleys, Jørgensen and Sandersen (2006) up to three, and Kristensen et al (2007) between five and seven, generally based on cross-cutting relationships between the tunnel valleys. This study shows up to ten separate generations of cross-cutting tunnel valleys within individual datasets, and a minimum of four correlatable generations mappable across individual datasets in the entire northern half of the study area, both at over much greater extents than any previous work.

The presence of numerous generations of superimposed tunnel valleys in the central North Sea study area has a number of important implications for evaluating tunnel valley formation methods, and what their presence might imply about the configuration of ice-sheets in the North Sea during the Pleistocene. Firstly, the multiple generations account to some degree for the apparent complexity in plan-form of tunnel valleys noted in other works (e.g. the North American examples in Chapter 2), and are therefore important in rethinking the link between tunnel valley formation and their geomorphology. 3D seismic reflection data allows the tunnel valleys to be studied in
much more detail than in previous 2D 'grid-type' surveys, and their cross cutting nature and relationships to be more accurately examined. For instance, detailed work using 3D seismic data by Kristensen et al. (2007) found that individual tunnel valleys in the Danish sector of the central North Sea are relatively straight and lacking anastomosing branches, hence any planform complexity is actually a result of overprinting rather than intrinsic to formation. The presence of numerous generations of cross-cutting tunnel valleys must also be reconciled to the ice sheet(s) that necessitated their formation, in terms of configuration, timing and dynamics. In other words, observations of apparently dense tunnel valleys do not accurately reflect their time transgressive formation. Care must be taken to resolve the separate systems of tunnel valleys and consider their properties from this perspective.

Individual tunnel valleys were assigned to a particular generation based on a number of factors (as illustrated in the flow diagram, Figure 5.2), but principally using cross-cutting relationships, as the most robust criterion. For isolated tunnel valleys, not found to cross-cut other valleys or be themselves cross-cut, comparison of orientation and morphology with nearby tunnel valleys was used to assist in assigning to a generation.

Kristensen et al., (2007) assume that the tunnel valleys in their study area exhibit a dominant direction relative to the ice-sheet margin, and therefore limit their assignment of tunnel valleys to a particular generation based on plausible ice-sheet configurations. However, there is little evidence for the extent of pre-Weichselian ice limits in the central North Sea, and so any interpretation of the buried tunnel valleys in this study cannot rely on known ice margin positions to constrain tunnel valley configuration (see Chapter 3 and the final part of this Chapter for further discussion). Although a precise relationship between tunnel valley formation and ice sheet behaviour is as yet unclear, it is assumed in this study that at the scale of several to tens of kilometres (e.g. the distance between individual tunnel valleys), formation conditions were initially similar, and it is expected that the incision of tunnel valleys at the same time and in the same local area would show some similarity in direction. Furthermore, this study finds little evidence for any underlying controls, such as salt structures, faulting, or large pre-glacial valley systems, on tunnel valley morphology and direction north of 58°N, implying that ice-sheet behaviour and dynamics were solely responsible for the configuration of the observed buried tunnel valley systems (see Chapter 3.1 for more on
pre-glacial conditions in the central North Sea, Figures 3.1, 4.4 and 7.16 for details of the strata beneath the tunnel valleys including salt structures).

Figure 5.3 presents examples of straightforward cross-cutting relationships in timeslice and vertical section in Dataset A (for location see Figure 5.4). Within each dataset, every tunnel valley was assessed for cross-cutting relationships with its neighbours, and the results compiled in representative flow charts. During the work it became apparent that some generations of tunnel valleys could be traced across a number of adjacent datasets, providing regional control on tunnel valley generations.

The results of this analysis are presented both at local (~ 400 km²) and regional (~ 1000 km²) scales, and alternate configurations and the associated levels of confidence are discussed. This framework of separate generations of tunnel valleys forms the basis for the analysis of tunnel valley morphology, fill and formation in Chapters 6 and 7.

5.2 Tunnel Valley Generations – Local Scale

At the level of individual datasets, cross-cutting relationships between buried tunnel valleys display a high level of complexity and in some cases, there are a number of alternative configurations that may be possible. The results are presented below in detail for eleven datasets in the northern half of the study area (locations A to K in Figure 5.4a,b) and one in the south (location M in Figure 5.4c). Table 5.1 summarises the cross-cutting relationships and number of possible generations of tunnel valleys for each dataset. The reader is referred to Section 4.1.3 of this work for more information on the 3D seismic reflection datasets discussed in this section and to Section 4.2 for the methods used in interpreting and mapping the buried tunnel valleys.
Table 5.1 Summary of separation of tunnel valleys within Datasets A to J and M. Best interpretation of generations is based on factors discussed in text for each Dataset.

### 5.2.1 Dataset A – Illustration of Method

Dataset A is situated towards the western edge of the northern study area, (Figure 5.4b), and is used here to demonstrate the process of separating tunnel valleys into generations based primarily on cross-cutting relationships. Within the survey area of 700 km², approximately 600 km² of 3D seismic reflection data is of sufficient quality to image tunnel valleys, with resolution decreasing towards the east (see Table 4.1). 17 discrete tunnel valleys were recorded within the dataset, 5 of which can be traced into adjacent areas covered by 3D seismic datasets with bin spacing of 50 m or less, and also into the regional lower resolution cnsmerge dataset which covers the entire region. Figure 5.5 shows the result of mapping the margins of the tunnel valleys present within the dataset. Question marks indicate areas of complex or unresolvable cross-cutting relationships and asterisks are locations where the start or end point of a tunnel valley is unclear due to poor data quality or data resolution limits. All of the tunnel valleys appear to be incised from the same stratigraphic level, with the exception of tunnel valleys m, n, and o, which incise from a higher horizon, implying a minimum of two generations of tunnel valley formation for the area.
Dataset A is used to provide a clear example of the processes used when analysing the tunnel valleys recorded in this study with respect to their relative chronology and eventual assignment to a particular generation. Based solely on cross-cutting relationships, a multi-stage history is clear, but a single, unique interpretation of their relative timing cannot be resolved, as illustrated in Figure 5.6(a-g). Tunnel valleys a, b, and c (tva, tvb and tvc in Figure 5.5) are the oldest channels, as each is cross-cut at least twice, and by younger tunnel valleys which are themselves cross-cut at least once. Furthermore, their location in the most densely incised area of the dataset (as opposed to, for example, tvd) where relationships between individual tunnel valleys are relatively clear (as opposed to tvf) make them suitable for initial analysis. However, based solely on cross-cutting relationships it is not possible to develop a chronological relationship between the three, as none of them cross-cut one another. Thus, for tunnel valleys tva, tvb and tvc, there are seven possible configurations as illustrated in Figure 5.6a-g.

Next in the history, tve cuts both tva and tvb, while being incised by tvg and tvh. Based on these relationships it is clear that tva and tvb are both older than tve, while tve is older than tvg and tvh. However, with respect to tvg and tvh there is uncertainty as to whether they were active at the same time and incised in to tve contemporaneously or they formed sequentially in two separate phases (compare stages in Figure 5.6j and k).

As is clear from the above example, when there are a number of sub-parallel tunnel valleys which do not cross-cut each other the possible configurations quickly multiply. However when one considers grouping by common orientation and morphology (e.g. a and b; g and h) and omitting valleys with unclear relationships to the main, central, group of tunnel valleys then the exercise is simplified and for Dataset A, five generations of tunnel valleys can be defined with a high degree of confidence. Figure 5.7(i - v) shows the sequence of incision, with Figure 5.7i showing the oldest generation of tunnel valleys (in red), and Figure 5.7v the youngest (blue). In a more conservative approach, based on dissimilarities between orientations, two extra stages might be added: Firstly, the configuration shown Figure 5.7i could be split into two stages, with tva and tvb grouped together, but tvc separately as it displays a different preferred orientation (mean resultant direction for tvc as measured in Section 4.2 is 136/316°). However, there is no indication as to the age relationship between a
generation containing tvc and that containing tva and tvb (mean resultant direction 024/204°). Secondly, the youngest generation of tunnel valleys in Figure 5.7v could also be split into two stages, due to the difference in orientation and morphology of tvo (mean resultant direction 013/193°) to tvn and tvm (mean resultant direction 106/286°). Again, a lack of interaction between tvo and tvn and tvm means that no conclusion can be drawn about their relative ages. Tunnel valleys in Dataset A which are poorly resolved, or those which display ambiguous relationships may also be incorporated to a lesser degree of certainty. For example, tvi is cut by tvh and tvh, and has a similar orientation to tva and tvb, placing tvi with the oldest generation of tunnel valleys (Figure 5.7i). Tunnel valleys tvd, tvk, and tvj could be added to the second oldest generation (Figure 5.7ii) due to their similarity in orientation to tve and tvf, and the incision of tvk, tvi and tvj by tvh and tvp. In this case, the separation of the tunnel valleys in Dataset A would lead to a seven-generation model of tunnel valley incision, as in Figure 5.8(i-vii).

Tunnel valley relationships in Dataset A are summarised in a flow diagram (Figure 5.9a) which illustrates the degree of uncertainty in assigning a valley to a particular generation. In the flow diagram the oldest valleys (Generation 1) are at the base, and the youngest generation (Generation 6) at the top. Cross cutting relationships are indicated with a solid line, tunnel valleys which are tentatively assigned to a generation are followed by a question mark and may be placed between generations. Stratigraphic horizons are marked by dashed lines. This type of diagram also clearly identifies valleys that could be assigned differently. Figure 5.9b provides an example of incision from a higher stratigraphic level for tvo in Dataset A.

5.2.2 Dataset B

Dataset B is situated to the east of Dataset A and contains approximately 600 km² of 3D seismic reflection data in which tunnel valleys are imaged (see Table 4.1 and Figure 5.4b). Within the dataset, 16 discrete tunnel valleys were identified, 9 of which can be traced into one or more adjacent datasets. Figure 5.10 displays the outlines of all the tunnel valleys in the dataset: asterisks indicate locations where the start or end of an individual tunnel valley is unclear and question marks indicate areas where tunnel valley relationships cannot be resolved or are uncertain. The large tunnel valley running approximately north to south through the centre of the dataset, tvm, is shown as pale grey and transparent in order to clarify its relationship to the tunnel valleys which it
cross-cuts and re-occupies. In the case of re-occupation, where a younger tunnel valley is clearly seen to follow the path of older tunnel valleys, the relationship is generally classified as cross-cutting, but may be investigated further in terms of morphology and fill (see Chapters 6 and 7).

The south-eastern part of Dataset B provides the basis for the separation of tunnel valleys in the dataset into generations, with straightforward cross-cutting relationships between tunnel valleys a to e (tva, tvb, tvc, tvd, tve). However, tunnel valleys i to l (tvi, tvj, tvk, tvl), which are re-occupied by tunnel valley m (tvm), are more difficult to assign to a generation with certainty, as they do not cross-cut any adjacent tunnel valley nor one another. The relationship between tvl and tva is also uncertain. Tunnel valley f (tvf) and tunnel valley g (tvg) are also relatively isolated and difficult to incorporate into a particular generation. Tunnel valleys o and p (tvo and tvp) are seen to incise from a higher stratigraphic level, confirming their status as the youngest generation of tunnel valleys. Figure 5.39 shows the reoccupation of tunnel valleys tvi and tvj in Dataset B by tvm, and also the base of tvo incising from a higher stratigraphic level. Figure 5.11(i-viii) shows an eight-generation configuration for Dataset B, with tvi tvj and tvk assigned tentatively assigned to the third generation in Figure 5.11 iii.

Within this configuration, tunnel valleys i through k form a westward-curving line through the centre of the dataset, later re-occupied wholly by tvm whose margins coincide with the lateral limits of underlying valleys (Fig 5.10 and Fig 5.11vi). Their relationship to one another and other adjacent tunnel valleys is unclear, except that tvk is seen to cross-cut tva. If grouped together, and in terms of orientation, their change in direction from north to south (i.e. approximately NNE/SSW to NNW/SSE over 25 km) matches that of tunnel valleys g and f (tvg and tvf). If tvi to tvk are then associated with tvf and tvg, we can place them as older than tve and younger than tva, therefore in Generation 3 or 4 (Figure 5.11ii or iii). However, in terms of orientation, tvi to tvk do not share similar characteristics to either tvd or tvb, which define generations 2 and 3 in terms of cross-cutting. A solution would be to add an extra generation for tunnel valleys tvi to tvk and tvf and tvg, but this would result in a generation not constrained by at least one secure cross-cutting relationship, which is to be avoided. Figure 5.12 illustrates the cross-cutting relationships within Dataset B that lead to a minimum of eight generations of tunnel valleys, regardless of the assignation of tvi to tvk and tunnel
valleys tvf, tvg, tvo and tvp. Those tunnel valleys whose assignments are uncertain are marked with a question mark, and tvi to tvk and tvf and tvg are grouped together with arrows indicating a range of possible generation assignment.

5.2.3 Dataset C

Dataset C is situated to the south east of Dataset B, with a survey extent of ca. 700 km$^2$. Tunnel valleys are well imaged over approximately 600 km$^2$ of this dataset. Bin spacing is 25 m (Table 4.1, Figure 5.4b). Dataset C displays a complex pattern of 21 tunnel valleys, with multiple instances of re-occupation in the central part of the survey, and many poorly imaged tunnel valleys towards the eastern half of the dataset area. In particular, two areas to the north and south of the dataset, circled in Figure 5.13, proved difficult to interpret in terms of tunnel valley generations. A large NE/SW trending tunnel valley, tvu (shown as orange in Figure 5.13) is seen to reoccupy several of the central tunnel valleys and can be found extending to the NE of this dataset. Its extent towards the south-west is uncertain.

To the west of the dataset, the relationship between tunnel valleys tva, tvb, and tvc are straightforward, with tva the oldest, cross-cut by tvb, which is cross-cut by tvc. In the central area, tunnel valley tve (outline is dashed) is re-occupied by tvf, which in turn is re-occupied by tvu where it anabranches to the east. Tunnel valley tvg, which cross-cuts tvd, is also re-occupied by tvu. Similarities in orientation between tvd, tve, tvf, tvg and tvu suggest that the former four comprise a suite of tunnel valleys whose paths were then later re-used by tvu, with tvd and tve being the oldest of the group. Tunnel valleys tvh and tvi are clearly cross-cut by tvg, and later by tvu, but differ significantly in orientation from the tvd-tvg suite. To the south-west, the relationship between tvj, tvk, and the reoccupied tunnel valleys and tvu is unclear, although it seems likely that the edges of tvu were constrained by the margins of then underlying tvj and tvk valley systems to the south-west.

Tunnel valleys tvl and tvm are clearly cross-cut by tvu, as are tvq, tvr and tvs. Tunnel valley tvo is cross-cut by tvn, but a lack of interaction with adjacent tunnel valleys makes it difficult to place within a generation. Tunnel valley tvp is poorly imaged within the dataset, with unclear start and end points, and cannot be included with any certainty within the interpretation. Tunnel valley tvt appears to be cross-cut by tvu, but the relationship is rather unclear. Given the complexity of the cross-cutting relationships
within the dataset, the four generations of tunnel valley incision presented for Dataset C in Figure 5.14(i-iv) are tentative, and most likely a cautious underestimate. Figure 5.15 presents the results of separating the tunnel valleys into generations, those assigned tentatively are followed by a question mark.

Although initial attempts at analysis of tunnel valley generations within Dataset C found a lack of evidence for a confident separation, tunnel valleys present in Dataset C were placed more confidently within a generation by utilising nearby overlapping datasets.

5.2.4 Dataset D

Dataset D is located to the south-east of Dataset C and its survey size is approximately 900 km$^2$, with a bin size of 25 m (Table 4.1, Figure 5.4b). The dataset contains 17 discrete tunnel valleys (Figure 5.16), four of which can be traced into adjacent datasets. Tunnel valley overprinting in Dataset D appears to be less dense than in those datasets to the west, and the dataset contains a number of relatively isolated tunnel valleys which were not assigned to a particular generation. Data quality and resolution decreases to the east and north.

Figure 5.17(i-vi) shows the results of separating the tunnel valleys in Dataset D into six generations based on cross-cutting relationships, with some tunnel valleys assigned a generation due to similarities in orientation. It is possible to interpret up to nine generations within Dataset D, if individual tunnel valleys with slight variations in orientation are used to define a single generation. For example, the configuration shown in Figure 5.17v could be split into two stages, with the incision of tvh and tvi separately. Conversely, unassigned tunnel valleys could be added to some generations, as in the case of tvp, which shows similarity in orientation and morphology to tvl and tve, both of which define a generation. However, a lack of any cross-cutting control for tvp precludes its assignment, as does the relative isolation of tvo and tvn. Figure 5.18 illustrates the cross-cutting relationships which result in a six-generation model for Dataset B, with some indication of those tunnel valleys which are not included in Figure 5.17.
5.2.5 Dataset E

Dataset E is situated to the north-east of Dataset D and east of C and contains 480 km² of 3D seismic reflection data. Bin spacing is 25m (Table 4.1, Figure 5.4b) but data quality is generally poor within this survey area, and only four buried tunnel valleys were recorded. However, three of the tunnel valleys can be traced outwith the dataset, and provide an important control on the regional generations of tunnel valleys discussed in the next section of this chapter. Figure 5.19a shows all of the tunnel valleys recorded in the area and Figure 5.19b their cross-cutting relationships where resolvable.

5.2.6 Dataset F

Dataset F is located to the east of Dataset G, and north of E, and overlaps with the eastern part of Dataset I (Figure 5.4b). The survey area is approximately 1200 km², and tunnel valleys are imaged in ca. 450 km² of 3D seismic reflection data with a bin spacing of 25 x 25 m.

Thirteen discrete tunnel valleys were imaged within Dataset F, six of which can be traced into adjacent datasets, specifically Datasets G and I (Figure 5.4, 5.20). There are some problems encountered in considering tvn, as in Dataset G and I it can clearly be seen incising from a higher stratigraphic level. Its extent and relationship to tvi is not clear within Dataset F, however, and thus it is not included in the tunnel valleys in this dataset into generations. Disregarding tvn, cross-cutting relationships were used to separate the tunnel valleys in Dataset F into at least six generations, as in Figure 5.21 i – vi. Towards the north of the dataset, there is some uncertainty regarding the relationship between tvg and tvh, therefore the configurations shown in Figure 5.21 iii and iv may be interchangeable. More generations may be interpreted within Dataset F if the tunnel valleys seen in Figure 5.21 iii are separated, although their similarities in orientation and form suggest they are part of the same generation. Figure 5.22 details the cross-cutting relationships used to interpret six generations of tunnel valleys for Dataset F and specifies which tunnel valleys (those followed by a question mark) were assigned a generation due to a similarity in morphology or orientation.

5.2.7 Dataset G

Dataset G is situated in the central part of the northern study area in Figure 5.4b, where its northern half overlaps the eastern part of Dataset I (Figure 5.4b). Dataset G comprises approximately 360 km² of 3D seismic reflection data, in which 13 individual
tunnel valleys were imaged (Figure 5.23). As before question marks indicate areas where the relationship between two or more tunnel valleys could not be ascertained, and asterisks mark the location of an uncertain start or end point for a single tunnel valley. The area to the north of the dataset inside the dashed circle proved difficult to interpret, due to the high density of overlapping and cross-cutting tunnel valleys.

A minimum of six generations of tunnel valleys were found in Dataset G, based on cross-cutting relationships and similarities in morphology and orientation between individual tunnel valleys (Figure 5.24 i-vi). One of the generations (as in Figure 5.24v) is defined by three tunnel valleys, tvg, tvh, and tvi, which are seen to reoccupy older tunnel valleys. Their extents and relationships to one another are unclear although it seems likely that these three tunnel valleys were part of a single system which trended broadly north-east to south-west and re-occupied older tunnel valley reaches. Tunnel valleys tvj and tvk (tvn in Dataset F as discussed above) are incised from a higher stratigraphic level and so define the youngest generation of tunnel valleys in the dataset although their variation in orientation suggest they may have been formed during different periods of tunnel valley erosion, which would result in a seven-generation interpretation for Dataset G. Figure 5.25 shows the cross-cutting relationships used to construct the six generation interpretation, and includes tunnel valleys assigned to a generation on the basis of morphology and orientation.

5.2.8 Dataset H

Dataset H is situated to the west of Dataset I but tunnel valleys are only imaged in an approximately 700 km² area to the south-east of the dataset. Data quality in this survey is relatively poor, with a bin size of 50 m, and only five tunnel valleys were recorded with the detail necessary to interpret cross-cutting relationships (Figure 5.26a). Tunnel valley tvf was found to be unique in comparison to the other valleys in the northern study area datasets in that it appears to incise from a lower stratigraphic level than otherwise observed, confirming its assignment as the oldest tunnel valley in the region. Figure 5.27a shows a portion of tunnel valley tvf as imaged in timeslice within the 3D seismic data, and Figure 5.27b illustrates the tunnel valley in section where an anastomosing part of its reach can be seen to incise from a lower stratigraphic horizon than that of the nearby tunnel valley tve. The remaining tunnel valleys in the dataset can be separated into three subsequent generations based on cross-cutting relationships as in Figure 5.26.
5.2.9 Dataset I

Dataset I is a large (3750 km\(^2\)) dataset to the north of the study area, in which a very dense, complex network of cross-cutting tunnel valleys are imaged (Figure 5.1a and b, Figure 5.4b for location). The tunnel valleys in the western part of the Dataset I were examined and assigned to cross-cutting generations. Those to the east were better imaged in Datasets F and G, and have been described above. Seventeen tunnel valleys were mapped in the western half of the dataset, four of which can be traced with certainty outwith the dataset to the south and west (Figure 5.28).

Based on cross-cutting relationships, up to eight generations of tunnel valleys are present in Dataset I, as in Figure 5.29 (i – viii). Some tunnel valleys were assigned to a generation based on similarity in orientation and morphology to those which defined a generation due to cross-cutting, indicated in Figure 5.30 by a question mark. Some difficulty was encountered while interpreting the margins of tvm, which, at its central part, appears to be re-occupied at least partially by a younger tunnel valley, tvn, which extends along the eastwards branch of the older tunnel valley (Figure 5.28). This relationship is interpreted as an independent generation in Figure 5.29viii and in Figure 5.30 but if taken as a reoccupation of tvm during one generation, seven cross-cutting generations can be interpreted.

5.2.10 Dataset J

Dataset J is situated to the west of Dataset K, at approximately 1°W. The survey area contains only partial 3D seismic reflection coverage, the best of which is in its north east corner, where seven cross-cutting tunnel valleys have been identified in an area of approximately 350 km\(^2\). Although relatively isolated from the central datasets in this region (Datasets A-G), some of the tunnel valleys can be traced into adjacent areas with the use of the cnsmerge dataset which extends over the whole area, and then integrated into the regional synopsis of tunnel valley generations presented in Chapter 5.3 (for location see Figure 5.4b).

It is possible to separate the tunnel valleys in Dataset J into a minimum of four cross-cutting generations as in Figure 5.31. The assignment of tunnel valley tvc is problematic, as it is possible that it could be part of either of the generations which cross-cut tva, either at stage ii or iv of Figure 5.31b. Therefore, its outline is shown as
dashed from stages ii to iv, to indicate the possibility of its incision during these younger generations.

5.2.11 Dataset M

Dataset M is situated in the southern part of the study area, at approximately 1°E, 57°N (Figure 5.4c). It comprises ca. 1000 km² of 3D seismic reflection data in which buried tunnel valleys are present, and is also covered by the dataset cnsmerge. Fourteen buried tunnel valleys were identified within the dataset, the majority of which display a strong NNW-SSE preferred orientation, in contrast to the less organised tunnel valleys in the datasets to the north. The extensive anastomosing tunnel valley, tvk in Figure 5.32 (in orange), dominates the local area, and appears to be part of the youngest generation of tunnel valleys.

Four tunnel valleys, tva, tvb, tvc and tvm, trend at right angles to the dominant pattern (i.e. SW/NE) and are cross-cut by at least two generations of younger tunnel valleys, placing them as the oldest generation of tunnel valleys. The central region shown dashed in Figure 5.32, is somewhat problematic as the southern extent of tvk is unclear. It seems likely that tvj and tvl form part of the tvk network but the orientation and morphology of tvm suggests it is part of a different generation. An absence of cross-cutting relationships in this area and similarity in form to the SW/NE trending tunnel valleys places tvm with this older generation. Figure 5.33 displays the resultant three-generation interpretation based on the cross cutting relationships shown in Figure 5.34. Four generations of tunnel valleys could be proposed if tunnel valleys tvh and tvi were incised in a separate generation than tvk and tvl. However, there is no indication of cross-cutting between the two sets of tunnel valleys within the Dataset M or in cnsmerge and so further interpretation is not possible. Alternatively based on similarities of orientation and morphology, it is also possible that tvk and tvl were incised at the same time as Generation 3 at stage ii in Figure 5.33.

5.3 Tunnel Valley Generations – Regional Scale

In the northern half of the study area from approximately 0°E, 58°N to 1°E, 58°30’ a suite of eleven overlapping 3D seismic reflection datasets provides detailed coverage of dense networks of buried tunnel valleys (see Figure 5.4 for location). By mapping individual tunnel valleys across adjacent and overlapping datasets, and by referring to the extensive lower resolution cnsmerge dataset, that covers the entire area (see Figure
5.4, Figure 4.3), it was possible to identify regionally important cross-cutting tunnel valleys and use these to identify generations of cross-cutting tunnel valley systems that persist and are consistent over an area of ca. 120 x 120 kilometres.

As with the interpretation at the scale of individual datasets, tunnel valleys were assigned to a generation primarily on the basis of cross-cutting relationships and, to some extent, similarities in morphology and orientation. At least seven distinctive generations were recognised at a regional scale, and in most cases, these correlated well with the interpretation of the individual datasets described above. Fifteen key tunnel valleys which extend across multiple datasets are shown in Figure 5.35. These can be considered as ‘type’ examples of the generation to which they are assigned and are referred to in the text. Note for clarity not all the tunnel valleys assigned to the regional generations are shown in this diagram. However many more are illustrated in the time-sequences in Figure 5.36 and Figure 5.37, where individual tunnel valleys which were well-constrained within their local datasets were added to the regional generations based on similarities in cross-cutting relationships, orientation and morphology to the ‘type’ tunnel valleys shown in Figure 5.35. In general, a high level of confidence was attached to the assignment of the youngest and oldest generations of tunnel valleys, the ‘middle’ generations proved more difficult to assign with certainty and a number of different configurations are proposed. In particular, some difficulty arose when considering tunnel valleys which appear to have been re-occupied, and whether those that were re-occupied and the re-occupying tunnel valleys should be considered as separate generations, or represent a multi-stage process during one single generation. Thus, this framework suggests six generations of tunnel valley incision, but including a Generation 3.5 (re-occupied) which is intimately associated with the Generation 4 tunnel valleys which reoccupy it. If these two sets of tunnel valleys are considered separately, eight regional generations of tunnel valleys may be interpreted. Figure 5.38 shows the cross-cutting relationships between the regionally important tunnel valleys in Figure 5.35.

The generations of buried tunnel valleys within Dataset M show a more coherent planform than those further to the north, which may be a result of them lying closer to (and being more strongly influenced by) an ice sheet margin to the south, or may simply reflect a local trend. The implications of these factors are discussed further at the end of
this chapter and measurements for the morphology and orientation of the tunnel valleys in Dataset M are presented in Chapter 6.

5.3.1 Generation 1

One regional-scale tunnel valley, which can be traced across Datasets H and I and within the extensive merged dataset, cnsmerge, is identified as tv1a in Figure 5.35 and is apparently cut from a lower stratigraphic level than all of the other tunnel valleys in the northern study area. Evidence for this is provided exclusively within Dataset H (Figure 5.27), as the tunnel valley is poorly defined in Dataset I, where a younger tunnel valley (tv5a) appears to follow its former path and details of its incision are obscured. However, the stratigraphic evidence from Dataset H (discussed further in Chapter 7) is compelling, and the presence of even a single tunnel valley at a deeper stratigraphic level than otherwise observed is significant in terms of relative chronology for the remainder of the buried tunnel valleys discussed below. Thus, tv1a in Figure 5.35 is considered the oldest of the regional generations of tunnel valleys, termed Generation 1 in this framework. No other tunnel valleys are seen to incise from this lower stratigraphic level. The morphology and stratigraphy of tunnel valley tv1a are discussed further in Chapters 6 and 7 of this thesis.

5.3.2 Generation 2

In the northern half of the study area comprising Datasets A to K (Figure 5.4b), a widely recognised regional generation of tunnel valleys are defined as Generation 2 and are based on the key tunnel valleys, tv2a and tv2b, identified as type examples for this generation as in Figure 5.35. Additional (local) tunnel valleys (Figure 5.36) were assigned to this generation on the basis of cross-cutting (all of the Generation 2 tunnel valleys are cross-cut at least twice by valleys which also cross-cut one another), which proved straightforward in comparison to separating the multiple generations of overlying tunnel valleys. No assignment was made on the basis of form or direction. Figure 5.36 shows the results of separating out this Generation 2; similarities in morphology and orientation are immediately apparent and are discussed in the next chapter of this work.

5.3.3 Generation 3

Tunnel valleys were assigned to the regional generation, Generation 3, based primarily on cross-cutting relationships with Generation 2. All seven tunnel valleys within this
generation are seen to cross-cut Generation 2 tunnel valleys, and all are cross cut by a number of younger generations as defined in this framework (Figure 5.36). Some tunnel valleys were associated with this generation due to similarities in morphology and orientation. The three key tunnel valleys used to define this generation: tv3a, tv3b and tv3c are shown as yellow in Figure 5.35.

5.3.4 Generation 3.5 – re-occupied generation

To the east of the northern study area, in Datasets B, C, F and G, a number of tunnel valleys are seen to be wholly or partially reoccupied by younger generation of wide, shallow tunnel valleys which are identified as Generation 4 within this regional framework (Figure 5.36). Figure 5.39 shows an example from a 3D seismic cross-section of a typical reoccupation in Dataset B (Figure 5.10) where the smaller, older tunnel valleys tvl and tvj (bases in white) are reoccupied by the larger tunnel valley tvm (base in red). As is apparent in both Figure 5.10 and Figure 5.39, the younger tunnel valley tvm does not simply cross-cut the older tunnel valleys, but follows part or all of their former path, defining the relationship as reoccupation rather than straightforward cross-cutting. The re-occupied set of tunnel valleys are represented within the key regional tunnel valleys by tv3.5a in Figure 5.35 (part of which is defined by tvl in Dataset B as in Figure 5.39), and shown in their entirety in Figure 5.36. The relationship between the re-occupied Generation 3.5 and Generation 5 (Figure 5.37) is not always clear, due to the influence of the reoccupying generation itself (Generation 4 in this framework). The re-occupied set (Generation 3.5) are occasionally cross-cut by the tunnel valleys defined as Generation 5 within this framework (type valley is tv5a in Figure 5.35). The limited extent of the tunnel valleys assigned to Generation 3.5, and uncertainty regarding whether re-occupation is sufficient to define a discrete generation of tunnel valleys (discussed further in Chapters 6 and 7) prevents definitive identification as a discrete generation. However, the characteristic morphology (see Chapter 6) and undeniable association with Generation 4 indicates enough individuality within the region to assign them tentatively to a place in the framework between Generation 3 and Generation 4.

5.3.5 Generation 4

Towards the central and eastern part of the study area, in Datasets B, C, G, and F, a number of large, shallow tunnel valleys can be identified which partially or wholly re-occupy southwards trending older tunnel valleys in Generation 3.5, (Figure 5.36,
These tunnel valleys have been grouped together into a single generation based both on their cross-cutting/reoccupying of a particular set of older tunnel valleys (Generation 3.5) and by their similarity in morphology and orientation. The tunnel valleys identified as part of this generation are all cross-cut by at least two generations of younger tunnel valleys, placing them near the middle of the regional generational framework. A feature to note is that they appear to converge southwards.

Some problems arise when considering the continuation of the tunnel valley identified as tv4a in Figure 5.35 (tvh in Dataset G, Fig 5.23, and tvm in Dataset B, Fig 5.13) into Dataset C, where it is expected to follow the path of tvb (Fig 5.14) and possibly interact with tv5a as shown in Figure 5.35. However, it appears that tv5b cross-cuts tv4a in Dataset C, and so the re-occupation by Generation 4 either halted suddenly to the south, or is related to a change in data quality across dataset borders. The abrupt termination of the valley at the boundary of Dataset C suggests the latter explanation is viable, although the former scenario could be envisaged if the re-occupation of Generation 3.5 by Generation 4 was being carried out as tv5a was formed, which then became the main conduit for drainage in the area. Unfortunately, the relationship between tv5a and tv4b, which extends further southwards, is ambiguous - the southern extent of tv4b being obscured in the dataset cnsmerge in which it is imaged.

### 5.3.6 Generation 5

A fourth regional generation of tunnel valleys is associated with the large branching tunnel valley tv5a (purple) in Figure 5.35. These tunnel valleys (shown in Figure 5.37) clearly cross-cut Generation 3 and 3.5 tunnel valleys in the western half of the northern study area, and tv5a is seen to cross-cut tv4a, which re-occupies older channels towards the south of the study area in Dataset C. The extent of the Generation 5 tunnel valley tv5a to the south west (in Dataset H) is ambiguous, it appears to have followed a similar path to that of the oldest tunnel valley, tv1a, and may have been reoccupied by a younger tunnel valley in its upper part.

### 5.3.7 Generation 6

A number of tunnel valleys are seen to cross-cut generations 1 to 5 but not to incise from a higher stratigraphic level as are those defined in Generation 7. This set of tunnel valleys, referred to as Generation 6, are similar to the type tunnel valley tv6a (brown) in Figure 5.35, and are shown as in Figure 5.37. There is some uncertainty as to their
relationship with one another, due to their widely varying morphology and orientation, but all clearly incise Generation 5 tunnel valleys.

5.3.8 Generation 7

The youngest generation of buried tunnel valleys in the regional framework is defined by seven tunnel valleys which were selected from those datasets (A, B and G) where they were seen to incise from a higher stratigraphic level (see examples in Figure 5.9 and Figure 5.39). Differences in data quality, seabed multiples, and static shifts between the individual dataset prevents this surface from being mapped in detail to provide evidence that the tunnel valleys were incised contemporaneously (see Chapter 4 for data problems and Chapter 3 for more information on regional stratigraphy), but given that the vast majority of tunnel valleys within each dataset in this area are seen to incise from the same horizon, it is implied here that those incising from a higher horizon are likely to be associated with one another.

It is very likely that a number of other tunnel valleys in the region also incise from a higher stratigraphic level and may be associated with this generation. A number of works, including those originally carried out by the BGS using 2D seismic profiles (see Chapter 3 for more details) described tunnel valleys incising from varying stratigraphic levels. It may be possible, for example, to include tvn from Dataset B (Figure 5.10) within Generation 7, as it shares very similar morphological characteristics to the tunnel valleys in this generation and the level from which it incises is ambiguous. Similar reasoning also places tvp from Dataset A as part of this generation (Figure 5.5).

5.4 Implications of Multiple, Cross-cutting Tunnel Valley Generations

A flowchart presenting the cross-cutting relationships between the key regional tunnel valleys in the northern half of the study area (Figure 5.35), which leads to the seven-generation regional framework as discussed above, is presented in Figure 5.38.

Considering the separation of tunnel valleys both locally and regionally results in the conclusion that a minimum of four, and a maximum of nine generations make up the dense networks of buried tunnel valleys observed within the 3D seismic reflection datasets in the central North Sea. This range of tunnel valley generations has a number of implications for the study of tunnel valleys, both in the North Sea and elsewhere, particularly with respect to their morphology and appearance, relationship to glaciations
and ice margins, and their methods of formation. Figure 5.40 shows the results of this work in the central North Sea in comparison with the works of Lonergan et al., (2006) and Kristensen et al., (2007) which shows the much greater extent of the data available, and the regional significance of the generational framework. Figure 5.41 places these works and that Praeg (1996) within the surrounds of the North Sea and the generally accepted Pleistocene ice limits (Sejrup et al., 2001; Ehlers and Gibbard, 2004). The rest of this work, presented in Chapters 6, 7 and 8, consider the buried tunnel valleys in the central North Sea in the context of the generational framework presented above, and with respect to the implications discussed below.

5.4.1 Morphology and Form

By separating the dense network of tunnel valleys observed within the central North Sea into separate generations, some of the apparent complexity of tunnel valley planform is accounted for. There is a corresponding reduction in evidence to support formation mechanisms which rely on the presence of widespread anastomosing, branching and braiding patterning within observed tunnel valleys. For example, the ‘similarity of form’ arguments used in North American to compare tunnel valleys forms to scabland features and thus imply formation by catastrophic release of meltwater (e.g. Fisher et al., 2005) are weakened (see Chapter 2.2.3 for more on this argument). As in the work of Kristensen et al., (2007), this study finds that the majority of tunnel valleys, especially in the northern study area, display relatively straight, isolated channels in plan form. Chapter 6 in this work examines the relationship between tunnel valley morphology, generation, and formation in more detail, but the generational framework outlined here is crucial in interpreting the form of the observed tunnel valleys in a meaningful way.

5.4.2 Glaciations in the North Sea

Perhaps the most crucial consideration relating to the separation of the tunnel valleys in the central North Sea into multiple cross-cutting generations is how this configuration arose with respect to the widely accepted three-fold model of Mid-Pleistocene glaciation in the region and in north-west Europe in general (summarised in Chapter 3, see Fig 3.1). Even incorporating uncertainties regarding the exact number of tunnel valley generations separated within each dataset and at the regional scale, this work provides strong evidence that at least seven discrete episodes of tunnel valley incision took place in the central North Sea between the Brunhes-Matuyama magnetic reversal
(ca. 0.78Ma B.P) and the onset of the Weichselian glaciation (ca. 70ka B.P). The current model suggests only two full glaciations of north-west Europe during this time, where ice limits in the central North Sea were uncertain at best (Ehlers and Gibbard, 2005, see Chapter 3, Figure 3.1). These observations highlight two issues: first, as to whether a single generation of tunnel valleys forms during a single glacial cycle; second, as to how the buried tunnel valleys in this study were formed with respect to ice-margin locations during the Mid-Pleistocene.

The key argument when considering the relationship between the observed tunnel valley generations and the Pleistocene glacial history of the North Sea is whether each generation represents an entire glacial cycle, or if multiple generations of tunnel valleys can be formed during advance and retreat of an ice sheet during a single glaciation. If the former argument is correct, then the current model of two single-stage glaciations between MIS 12 and 5e (i.e. the Elsterian and Saalian glaciations) is an underestimate, and the sequence of buried tunnel valleys in the North Sea preserves the evidence for at least seven glaciations within this time period. As is discussed in Chapter 3, there is some evidence to support a number of pre-Elsterian glaciations of the North Sea, and the recent work of Lee et al., (2002) can be used to support an extensive MIS 16 glaciation, during which a generation of tunnel valleys may have been formed in the central North Sea.

The incision of tv1a (Figure 5.35) from a lower stratigraphic level, as identified in Figure 5.27, may also suggest that this tunnel valley was formed in a pre-Elsterian glaciation, a significant hypothesis which is considered more fully in Chapter 7. In any case, the timing and extent of both the Elsterian and Saalian glaciations is by no means well established for the central North Sea, and the oxygen isotope curve for the region (see Figure 3.2) could support a number of cold periods between MIS 16 and 5e during which ice cover over the central North Sea is conceivable. The rest of this work considers the multiple generations of tunnel valleys as possible evidence for such additional glaciations and Chapter 9 summarises their formation with respect to the Quaternary of the North Sea.

An alternative explanation for the numerous generations of tunnel valleys is that they formed during the two accepted Mid-Pleistocene glaciations and that ice cover during
these times varied sufficiently to account for the differences in form and orientation of the cross-cutting generations. Recent work on the Weichselian glaciation (Carr et al., 2006; Graham et al., 2006; Graham, 2007; Bradwell et al., 2008) supports a multi-stage model for the LGM, with a number of significant ice advances and retreat, but the seabed tunnel valleys related to this glaciation display a relatively simple morphology; within the central North Sea the tunnel valleys are evenly distributed and generally straight for most of their reach, with a strongly preferred orientation in direct contrast to the more complex generations of buried tunnel valleys. Chapter 8 in this work discusses their morphology more fully, but it can be concluded here that none of the seabed tunnel valleys display cross-cutting relationships with one another, and there is no evidence that the seabed tunnel valleys have been re-used or modified by an ice sheet displaying a significantly different configuration than that which formed the tunnel valleys. The single generation of seabed tunnel valleys and their simple morphology associated with the LGM ice-sheet advance and retreat is in marked contrast to the multiple generations and complex, cross-cutting geometries of buried tunnel valleys documented here. This observation does not support the notion that the multiple generations of buried tunnel valleys were formed during a single glaciation, even if ice margin fluctuation occurred. In other words, seven generations of tunnel valley are unlikely to have been formed during only two glaciations, even if those ice-sheets oscillated significantly during those glacial episodes.

The difference in morphology between the seabed and buried tunnel valleys, even when the latter are separated into generations which display more coherence in form, is also significant when considering the relationship of the buried tunnel valleys to the ice margin during their formation. As outlined in Chapter 2 of this work, the majority of tunnel valleys studies relate their location to a clearly defined ice margin, whether formation is by catastrophic or steady state processes. Even the recent work of Kristensen et al., (2007), which also finds evidence for cross-cutting tunnel valleys in a 3D seismic reflection dataset from the southern North Sea, separates generations of tunnel valleys with respect to a strongly defined ice margin to the south (see Figure 5.40, Figure 5.41 and Figure 3.1). The majority of the buried tunnel valleys in this work, however, are located some distance from the (inferred) ice margins during extensive Pleistocene glaciations, being situated hundreds of kilometres from the shelf break to the north and a similar distance from most projected ice margins to the south.
(see Figure 3.1, Figure 5.41). The individual generations of tunnel valleys defined in the northern half of this study show significant changes in direction between generations, which must be explained either by a changing ice margin position which influenced features hundreds of kilometres towards the centre of the North Sea, or by tunnel valley formation influenced by ice conditions towards the centre of the basin itself (as discussed further in Chapter 9). In either case, the precise location of the Mid-Pleistocene ice-sheet margins appears to be less influential on the formation of tunnel valleys in the central North Sea, and the rest of this work examines the tunnel valleys more closely within this context.

5.4.3 Mechanism of Formation

The separation of the buried tunnel valleys in this work into cross-cutting generations is significant not only with respect to the configuration and chronology of the ice sheets beneath which the tunnel valleys formed, but it also has a direct bearing on how the tunnel valleys formed. For example, the discovery of generations of tunnel valleys which appear (at both the local and regional scale) to re-occupy older systems raises questions about the preservation of tunnel valley generations in the landscape and the influence of associated remnant topography on later tunnel valley formation. What kind of formation processes would result in this configuration, and why does such re-occupation occur between some generations and not others? Similarly, why do the earlier regional generations of tunnel valleys consistently display a relatively straight, narrow and deep morphology in contrast to later generations of tunnel valleys? When considering the link between formation processes and morphology, the separation of the tunnel valleys into generations proves crucial in providing an appropriate genetic-stratigraphic perspective. The results presented in Chapters 6 and 7 on the morphology and fill of the buried tunnel consider the valleys within the context of the different generations identified here.

5.5 Conclusions

The results of separating the buried tunnel valleys as observed into this work into a number of generations at the local and regional scale can be summarised as follows.

- The extent and quality of the 3D seismic reflection data used in this work reveals complex networks of buried tunnel valleys imaged within the central North Sea. Using cross-cutting relationships and similarities in morphology and
orientations, the tunnel valleys can be separated into a number of individual, cross-cutting generations.

- Within individual datasets (ca. 600 km²), up to 8 generations of cross-cutting tunnel valleys are interpreted, with most datasets displaying between 4 and 7 generations.

- The tunnel valley tv1a, which is found within Datasets H and I, is seen to incise from a lower stratigraphic level than all of the other buried tunnel valleys.

- By tracing tunnel valleys across overlapping datasets in the northern half of the study area, a minimum of seven generations of tunnel valleys are interpreted at the regional scale (ca. 200 x 200 km).

- The separation of the buried tunnel valleys in the central North Sea into discrete generations has important implications when considering the glacial history of the North Sea. This chapter presents the evidence for at least seven separate episodes of tunnel valley incision between MIS 16 and the onset of Weichselian glaciation. The prevailing model of glaciation in north-west Europe suggests that only two full glaciations occurred within this period. Therefore, the buried tunnel valleys either preserve evidence for further glaciations within this period, or they record significant oscillation of ice cover over the North Sea during the Anglian and Saalian glaciations.

- The buried tunnel valleys in this study are located some distance from the traditionally accepted ice margins of the North Sea during the Pleistocene (see Figure 3.1, Figure 5.41), and their separation into individual generations with widely varying orientations and morphologies suggest that these tunnel valleys are not influenced by an adjacent ice sheet margin, in contrast to the inferences made by other works on tunnel valleys (e.g. Kristensen et al., 2007). The rest of this work therefore considers the influence of ice margins (in the widely-accepted sense) on the buried tunnel valleys of the central North Sea to be minimal.
The presence of individual generation of tunnel valleys with significantly different character and form also has implications for the formation mechanisms of the tunnel valleys themselves. Chapters 6 and 7 of this work therefore consider the morphology and fill of the buried tunnel valleys in the context of the generational framework outlined in this chapter, as well as the debate between catastrophic and steady-state formation for the buried tunnel valleys in the central North Sea.
5.6 Chapter 5 — Figures

Figure 5.1a Complex networks of tunnel valleys imaged at 364 ms TWTT in Dataset I (see Figure 5.4 for location). The line a–a’ indicates the location of the profile in Figure 5.1b.
Figure 5.1b Seismic profile a-a’ (see Figure 5.1 for location) across Dataset I illustrating the complexity of tunnel valleys in the area in section.
Figure 5.2 Process diagram for assigning individual tunnel valleys to a generation. Cross cutting relationships between tunnel valleys provide the best control on assignment, followed by similarities in orientation between individual tunnel valleys. Isolated tunnel valleys are placed less confidently within a generation, and those which are poorly resolved in the data may be overlooked. Within this work, tunnel valleys are only confidently assigned to a particular generation if they are cross-cut by at least one younger tunnel valley, and display a similar orientation to those within the same generation.
Figure 5.3 Tunnel valleys imaged in timeslice and vertical cross-profile in Dataset A. Cross-cutting relationships between tunnel valleys are visible between tunnel valleys a to f (i.e. c cross-cuts d and a, b cross-cuts a).
Figure 5.4 (a) Regional study area showing location of Figures 5.4a and 5.4b within the regional dataset cnsmerge. (b) Locations of 3D seismic surveys A-K in the northern part of the study area, referred to as "northern study area" in text. Buried tunnel valleys within the eleven surveys in blue are discussed in detail with respect to their assignment to locally cross-cutting generations of tunnel valleys. Locations of figures from this chapter are shown in red and pink.

Figure 5.4 (c) Location of 3D seismic survey M in the southern part of the study area, referred to as "southern dataset" in text. The blue outline shows the extent of the dataset cnsmerge in the region. The pink outline shows the area of the dataset where buried tunnel valleys were recorded and separated into cross-cutting generations.
Figure 5.5 Outline view of all tunnel valleys recorded in Dataset A (for location see Figure 5.4a). Tunnel valleys are labelled from tva to tvp and shaded in grey. Asterisks indicate locations where the start or end point of a tunnel valley is unclear. Question marks are placed in areas where cross-cutting relationships are ambiguous. For example, in the eastern part of this dataset it is not possible to resolve the southern extent of tvj and its interaction with tvp and tvh, although tvj is seen to re-occupy completely the northern half of tvi. The line a-a’ shows the position of the seismic profile in Figure 5.9b.
Figure 5.6 Possible sequences of tunnel valley incision for dataset A. Figures (a) to (g) show all possible configurations for tunnel valleys a, b and c (tva,tvb,tvc) as the oldest tunnel valleys in the area, either incised contemporaneously (a), independently (b-d), or in combination (e-g). (h) to (i) displays tve (orange) as it cross-cuts tva and tvb (red) and then varying configurations for the younger cross-cutting tunnel valleys tvg and tvh (purple) as they incise tve either contemporaneously (k) or one at a time (i and j). The colours used in this diagram are consistent with those used for the assignation of generations in the rest of this work.
Chapter 5: Results — Generations of Buried Tunnel Valleys

Figure 5.7 (i to v) Five generations of tunnel valleys interpreted from Dataset A based cross-cutting relationships where stage i shows the oldest generation (in red) and v the youngest (in blue). Weighted orientation measurements are displayed as rose diagrams (outer circle equals a frequency of five) and mean directions are given based on the methods outlined in Chapter 4.
Figure 5.8 (i-vii) Seven-generation interpretation of tunnel valley relationships within Dataset A based on cross-cutting relationships, orientation and morphology of tunnel valleys, where stages i and ii show the oldest generation and vi and vili the youngest. Note that the relative age of stages i and ii cannot be deduced from tunnel valley relationships, nor can the relative age of vi and vili. The addition of tv i to stage ii and tvj and tvk to stage iii is tentative, as their interpretation within Dataset A is ambiguous.
Figure 5.9a Flow chart showing the assignment of tunnel valleys in Dataset A when separated into five generations, with generation one being the oldest, and five the youngest. Black lines indicate cross-cutting by the higher tunnel valley. Question marks indicate a tentative assignment, for example, tvk is cross-cut by tvg, which may place it within Generations 1 to 3. However, on the basis of its similarity in orientation and morphology, it is assigned to either Generation 1 or 2. Similarly, tvd is cross-cut only by tvn and tvm, both at a higher stratigraphic level, indicating it could be assigned to any Generation older that 5. However, its orientation suggests it is more likely to be a member of Generation 2.

Figure 5.9b Example of incision from a higher stratigraphic level for tunnel valley tvo (base in blue) compared to tvf (base in orange)in Dataset A. Location of profile a-a’ is show in Figure 5.5.
Figure 5.10 All tunnel valleys interpreted from Dataset B. Question marks indicate unclear relationships between tunnel valleys, asterisks indicate a location where the start or end point of a tunnel valley is ambiguous. Tunnel valley tvm is drawn as transparent in order to display the tunnel valleys it reoccupies beneath its path. The line a-b indicates the location of Figure 5.39 which shows the reoccupation of tvl and tvj by tvm in section.
Figure 5.11 (i-viii) Eight generations of tunnel valleys in Dataset B based on cross-cutting relationships, and similarities in morphology and orientation. In each stage, the tunnel valleys that define the generation are shown as light grey, any older tunnel valleys are shown as dark grey. Tunnel valleys tvf, tvg, tvi, tvj, tvk, tvl (see Figure 5.10) are not included as their cross-cutting relationships are not clear, as outlined in the text. Of note within this dataset is that many of the generations are dependant on just one tunnel valley with clear cross-cutting relationships to those above and below it.
Figure 5.12 Flowchart showing the assignment of tunnel valleys within Dataset B to Generations 1 through 8, based on the cross-cutting relationships between tunnel valleys shown by black lines. The dashed line represents a change in stratigraphic levels. Tunnel valleys displayed with a question mark indicate tentative assignments, for example, cross-cutting controls on tvi, tvj, tvk and tvl are limited to their all being cross-cut by tvm, and tvk cross-cutting tva. Therefore, with the exception of tvk, which is certainly younger than tva, all may only be assigned to generations older than tvm, i.e. Generation 1 to Generation 4. However, as the four tunnel valleys show similar orientations and morphologies to one another, and are all re-occupied by tvm, it is suggested they were most likely incised contemporaneously. Their similarity in orientation to tvf and tvg suggests they are younger than tve, which cross-cuts tvf, placing them within Generation 2 or 3. However, a lack of similarity between the unassigned tunnel valleys, and those which define Generations 2 and 3 means they cannot be placed more confidently without inferring further generations, not defined by at least one cross-cutting relationship. The range of possible generations to which they could be assigned is indicated by the vertical bar on the right of the diagram.
Figure 5.13 All 21 tunnel valleys recorded in Dataset C. Asterisks indicate locations where the start or end point of a tunnel valley is unclear, and question marks show where the relationship between one or more tunnel valleys is ambiguous or unable to be clarified. Due to the complexity of tunnel valleys in this dataset, and the influence of the large tunnel valley tvu (in orange), which re-occupies a number of older tunnel valleys, some areas of the dataset prove difficult to interpret with respect to cross-cutting. These areas are marked by dashed circles and some of the tunnel valleys within these areas have not been assigned to a particular generation with any degree of confidence.
Figure 5.14. Four generations of tunnel valleys interpreted from Dataset C, based on cross-cutting relationships and similarities in orientation and morphology. The small number of generations reflects the complexity of tunnel valley relationships in this study area, and is likely underestimated as some tunnel valleys (e.g. p, n, o) could not be easily included.
Figure 5.15 Flowchart showing four generations of tunnel valleys in Dataset C based on the cross-cutting relationships indicated by black lines. Those tunnel valleys followed by a question mark are assigned tentatively, on the basis of similarities in morphology or orientation with others in the same generation. In this dataset, it is likely that more than four generations of tunnel valleys are present, but a lack of clear cross-cutting relationships and a large proportion of isolated tunnel valleys (see Figure 5.14) prevents further separation.
Figure 5.16 All recorded tunnel valleys in Dataset D. Asterisks indicate locations where the start or end point of a tunnel valley is ambiguous, question marks show locations where the relationship between one or more tunnel valleys is unclear.
Figure 5.17(i-vi) The separation of tunnel valleys within Dataset B into six generations based on cross-cutting relationships, and to some extent, orientation and morphology. The isolated tunnel valleys tvn, tvo and tvp (see Figure 5.16) are included in this configuration with dashed outlines to illustrate their assignment with some uncertainty due to their relatively isolated location and the lack of a clear relationship between tunnel valleys n and m.
Figure 5.18 Flowchart showing the cross-cutting relationships (black lines) between the tunnel valleys in Dataset D, and their separation into six generations. Tunnel valleys followed by a question mark are allocated to a generation based on similarities in orientation and morphology to a particular generation, but assignment may be relatively tentative, as in the case of tvp and tvn which are isolated from the other tunnel valleys in the dataset. The relationship between tvp and tvn is also not clear.
Figure 5.19 (a) Configuration of the four cross-cutting buried tunnel valleys within Dataset E. Asterisks indicate locations where the start or end point of a tunnel valley is unclear. (b) Three generations of tunnel valleys separated in Dataset E, where tvc is associated with the first generation, defined by tva, due to their similarities in orientation. It is possible that tvc could also be assigned to the second generation with tvb, or have formed during a separate event before the incision of tvd, leading to a four-generation configuration for Dataset E.
Figure 5.20 Tunnel valley outlines as interpreted from Dataset F. Question marks indicate locations where the relationship between tunnel valleys is uncertain, for example, at the junction of tvi and tvj and between tvg and tvf. Tunnel valleys tvh, tvj and tvk are shown as transparent in order to indicate the path of the older tunnel valleys which they re-occupy. Tvn (in orange) appears at a higher stratigraphic level in Datasets G and I, which overlap this area, but it is not clear whether this also applies to tvi within this dataset. It is suggested that tvn reoccupies tvi only to the extent shown here, although this is not clear when examining the data. Hence, tvn is not included in the separation of tunnel valleys in Dataset F into cross-cutting generations.
Figure 5.21(i - vi) Six generations of tunnel valleys in Dataset F interpreted from cross-cutting relationships and similarities in morphology. The configurations at stages iii and iv may be interchangeable as the relationship between tvg and tvf is unclear due to the influence of tvh which cross-cuts both tunnel valleys and reoccupies part of tvf, as shown in stage vi.
Figure 5.22 Flow chart showing the cross-cutting relationships (black lines) between tunnel valleys in Dataset F resulting in the separation of six generations of tunnel valleys. Tunnel valleys followed by a question mark were assigned to a generation based also on similarities in morphology and orientation to those clearly defined by cross-cutting relationships. For clarity, not all cross-cutting relationships are illustrated if they are not required to define a generation. For example, tvf also cross-cuts tva, but the relationship is not included.
Figure 5.23 All tunnel valleys as interpreted from Dataset G. Question marks indicate locations where relationships between tunnel valleys are unclear, asterisks show where the start or end point of a tunnel valley cannot be determined. The dashed circle to the north of the dataset contains an area of complex overprinting, and the extent of tvc and its relationship with tvb, tvd and tvi is unclear. Tunnel valleys tvi, tvg and tve are shown as partially transparent to demonstrate their re-occupation of older tunnel valleys. It is likely these three tunnel valleys were part of one system but their relationship to one another cannot be determined from the current data. The location of BGS borehole 77/02 is also indicated.
Figure 5.24 (i - vi) Six generations of tunnel valleys interpreted from Dataset G based on cross-cutting relationships between individual tunnel valleys and similarities in morphology and orientation. Stage v in the figure shows three tunnel valleys which follow part of the reach of older tunnel valleys. It is likely these are part of a single system which reoccupied part of the older tunnel valleys; the exact configuration and extent of the reoccupying tunnel valleys are unclear.
Figure 5.25 Assignment of tunnel valleys from Dataset G into six generations based on cross-cutting relationships (shown as black lines). Generation 5, comprising tvg, tvh and tvi is seen to reoccupy a number of younger tunnel valleys, while tunnel valleys tvk and tvj are cut from a higher stratigraphic level, indicated by the horizontal dashed line.
Figure 5.26 (a) All tunnel valleys imaged within Dataset H, ambiguous start and end points are marked by asterisks. The location of Figure 5.27a which shows tunnel valley tvf in time-slice is shown as a black box, the line a-a’ shows the location of the section shown in Figure 5.27b. (b) Four generations (i-iv) of tunnel valleys interpreted from cross-cutting relationships in Dataset H. Note that tunnel valley tvf incises from a lower stratigraphic level than any of the other tunnel valleys in the northern study area, making it the oldest tunnel valley of all observed and implying a significant chronological gap between stages i and ii in the configuration envisaged in Figure 5.26b.
Figure 5.27(a) Timeslice at 344 ms TWTT showing sections of the tunnel valleys tvf and tve in planform within Dataset H. The anastomosing section of tvf is well imaged within the timeslice and joins the main section of tvf at a high angle. (b) Cross section of profile a-a' (location in Figure 5.26a) which clearly shows the incision of tunnel valley tvf from a lower (and therefore older) stratigraphic horizon (in red) than that of tunnel valley tve (in white). The three channels which make up part of tvf in planform (Figure 5.27a) are well-defined.
Figure 5.28 All tunnel valleys as identified in the western half of Dataset I. Asterisks indicate locations where the start or end point of an individual tunnel valley is unclear. Question marks show areas where the relationship between one or more tunnel valleys is ambiguous as in the case of tvn which appears to partially re-occupy the southern reaches of tvm. The extent of tvk to the south-west is also unclear, as the younger tunnel valley appears to follow the path of tvc and is difficult to trace outwith this dataset. The tunnel valleys to the east of the dataset are better imaged in Datasets F and G, shaded here in grey, and shown in Figure 5.20 and Figure 5.2.1.
Figure 5.29 (i-x) Eight generations of tunnel valleys in the western part of Dataset I based on cross-cutting relationships. Tunnel valley tvc in stage i appears to incise from a lower stratigraphic level in Dataset H (see Figure 5.27) to the west of Dataset I but this is not apparent in Dataset I, although it does appear to make up the oldest generation. The extent of tunnel valley tvn, which appears to re-occupy tvm, is also slightly unclear, and if it is incorporated into stage viii shown here, seven generations of tunnel valleys may be interpreted for Dataset I.
Figure 5.30 Flow chart showing eight generations of tunnel valleys within Dataset I based on cross-cutting relationships (black lines). Tunnel valleys followed by a question mark have been assigned to a generation based on similarities in orientation or morphology to those defined by cross-cutting. Tunnel valley tvn has been assigned to a separate generation due to its re-occupation of tvm, but could also be considered as part of Generation 7.
Figure 5.31 (a) Outline of all tunnel valleys imaged in Dataset J. (b) i - iv Four-generation model of tunnel valley incision for Dataset J based on cross-cutting relationships and similarities in orientation. Tunnel valley c is shown with a dashed outline to indicate its possible assignment to either stage ii or iv.
Figure 5.32 All tunnel valleys interpreted in Dataset M. Asterisks indicate the locations where the start or end point of a tunnel valley is unclear, question marks show where the relationship between one or more tunnel valleys is ambiguous. The two dashed circles border areas where interpretation is hampered by complex cross-cutting and overprinting. The southern extent of tvk (orange) is ambiguous, although it is likely that tvj is part of the anastomosing system, as is tvl.
Figure 5.33 i-iii Three generations of tunnel valleys in Dataset M based on cross-cutting relationships and similarities in morphology and orientation. A further stage can be envisaged if tvh and tvi are considered separately from tvk in what is presented here as one generation in stage iii. In the three-generation model, it is also possible that tvk may belong to the second generation, shown as stage ii in this diagram.

Figure 5.34 Flow chart showing cross-cutting relationships (black lines) between tunnel valleys in Dataset M resulting in the separation of three generations of tunnel valleys within the dataset.
Figure 5.35 Regionally important tunnel valleys in northern study area used as the basis for separation of generations. Tunnel valleys are separated into Generation 1 (grey), 2 (red), 3 (orange) 3.5 (pink), 4 (transparent green), 5 (purple), 6(brown) and 7 (blue) The extent of the dataset cnsmerge in the region, which covers the majority of the study area, is shown as dark blue. Tunnel valleys shown as transparent are seen to re-occupy younger tunnel valleys. Figures 5.36 and 5.37 provide further details of the individual generations.
Figure 5.36 (a - d) Five stages from the seven-generation regional interpretation of tunnel valleys identified within the northern study area and based on the type tunnel valleys shown in Figure 5.35 for each generation. (a) Generation 1 (tv1a in grey) and Generation 2 (in red), (b) Generation 3 (c) Generation 3.5, which is reoccupied by (d) Generation 4. Difficulties in resolving the cross-cutting relationship between Generations 3.5 and 4 prevent the former from being used to define an entirely separate generation. A sequence of tunnel valley incision could then be considered whereby stages c and d occurred in brief succession, and therefore comprise a single generation of incision followed by re-occupation.
Figure 5.37 (e - g) Three stages from the six-generational framework of tunnel valleys interpreted within the northern study area and based on the type tunnel valleys shown in Figure 5.35. (h) All six generations based on the assignment of 46 individual tunnel valleys into cross-cutting generations as typified by the key tunnel valleys shown in Figure 5.35.
Figure 5.38 Flow chart showing the assignment of the key regional tunnel valleys shown in Figure 5.35 into seven generations (1-7) of tunnel valleys based on cross-cutting relationships (black lines). Dashed horizontal lines represent stratigraphic horizons. Tunnel valley tv1a is seen to incise from a lower stratigraphic level (represented by the dashed line) in Dataset H only. Tunnel valley tv3.5a represents a set of tunnel valleys which are re-occupied by Generation 4 (dashed vertical line), and is assigned to a generation between Generations 3 and 4 to make clear the distinction between re-occupation and cross-cutting. For clarity, not all cross-cutting relationships are shown in this diagram if an intervening generation makes it clear that two tunnel valleys are from different generations. For example, tv6a is seen to cross-cut tv2a in Figure 5.35, but this is only implied by its cross-cutting of younger generations within this figure.
Figure 5.39 Cross section through the 3D seismic Dataset B (see Figure 5.10 for location of line a-b) illustrating the reoccupation of Generation 3.5 by Generation 4 in the regional framework. Two tunnel valleys in Dataset B (base in white), tvl and tvj, are clearly reoccupied by the larger tunnel valley tvm (base in red). Note that the margins of the younger tunnel valley broadly corresponds to the older tunnel valleys, indicating reoccupation rather than straightforward cross-cutting. Tunnel valleys tvl and tvm from Dataset B are also recognised as regionally important and form part of the tv3.5a and tv4a 'type' tunnel valleys in the regional generational framework shown in Figure 5.35. Also of note is tvo, which can be seen to incise from a higher stratigraphic level and is assigned to Generation 7 in the regional framework.
Figure 5.40 Summary map showing the central North Sea region and the result of the separation of buried tunnel valleys into seven generations in the northern half of the study area (Datasets A - J) and the interpretation of buried tunnel valleys in the southern Dataset M. Comparison with previous work on buried tunnel valleys carried out using 3D seismic data in the central North Sea by Lonergan et al. (2006) and Kristensen et al. (2007), shown boxed in red, highlights the much greater extent of this work. The dashed line to the south represents the maximum southern extent of the Weichselian ice sheet at LGM as proposed by Sejrup et al. (2000). Figure 5.41 shows the regional context of the work described here.
Figure 5.41 Summary map showing the location and results of mapping tunnel valleys in this work (outlined in black) and those from Lonergan et al., (2006), Kristensen et al., (2007) and Praeg (1996), outlined in red. The relative position of the Elsterian (orange), Saalian (green) and Weichselian (blue) ice limits are included from Ehlers and Gibbard (2004). The dashed blue line indicates the position of the southern margin of the Weichselian glaciation as suggested by Sejrup (2000).
Chapter 6: Morphology of Buried Tunnel Valleys

This chapter summarises the results of morphological measurements made for buried tunnel valleys identified within the 3D seismic datasets which make up the study area of this work as shown in Figure 6.1a. For the purposes of this chapter, the study area is split into a northern and southern part, with the dividing line at 57°30'N. Detailed morphological measurements for tunnel valleys in the northern study area were made from Datasets A – J (see Figure 6.1b for details). In the southern study area, only one 3D seismic dataset, Dataset M (see Figure 6.1a for location), was of sufficient quality to image tunnels in the detail required to compare their morphology to those in the northern part of the study area. The regional dataset, cnsmerge (Figure 6.1), was used to link the two study areas and, when data quality allowed, could be used to image and measure the planform morphology of the buried tunnel valleys over a larger area.

The first part of this chapter presents the results of morphological measurements for the northern part of the study area, while the second part details the results of morphological measurements made for Dataset M in the southern part of the study area. Morphological measurements from the regional dataset, cnsmerge, are also included where relevant. The resulting morphological measurements are then discussed with respect to the generations of cross-cutting tunnel valleys identified in Chapter 5, the variation of tunnel valley morphology within the study area with respect to location, formation processes, and finally, relationship to Pleistocene ice sheet dynamics and extent.

6.1 Northern Study Area

6.1.1 Analysis of Morphology

The results of the initial morphological analysis for the tunnel valley generations (including Generation 3.5) defined for the northern study area in Chapter 5.3 are presented in Table 6.1. Generation 1, which is based on a single tunnel valley (tv1a in Figure 5.35) is excluded for this reason and discussed later in this chapter. Details of the methods used for the width and sinuosity measurements are described in Chapter 4.2.2.1. Width to depth ratios (w:d) are given as a range for each generation. Errors for
width measurements depend on the lateral resolution of the individual datasets, but can be estimated as approximately ± 25 m, reduced further by multiple measurements.

<table>
<thead>
<tr>
<th>Regional Generation</th>
<th>Average Width (m)</th>
<th>Maximum Width (m)</th>
<th>Minimum Width (m)</th>
<th>Number of width measurements</th>
<th>Average Sinuosity width:depth (typical)</th>
</tr>
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<tbody>
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</tr>
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<td>60</td>
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<td>1928</td>
<td>342</td>
<td>53</td>
<td>1.106</td>
</tr>
</tbody>
</table>

Table 6.1 Summary of morphological measurements for the Generations 2-7 of tunnel valleys defined in Chapter 5.3. Note that Generation 1 is defined only by a single tunnel valley (tv1a in Figure 5.35 and is therefore not included.

6.1.1.1 Widths

Figure 6.2a shows a width histogram for all the tunnel valleys measured in the northern study area. The average width for all of the tunnel valleys is 1413 m, the maximum width observed is 7549 m and the minimum width 284 m (all with ± 25 m error). The median value for all of the tunnel valleys in the northern study area is 1034 m. From Figure 6.2, the most frequently measured widths are in the 800 - 900 m category and 1000 - 1100 m category (both with 68 observations out of 733) and in total, 96% of the measurements show widths between 300 and 3000 m. The skewed distribution in Figure 6.2a is largely due to the presence of 22 width measurements greater than 3000 m (3% of the total).

In order to ascertain whether the widths of tunnel valleys were significantly different between generations, an analysis of variance (ANOVA) test was used. The ANOVA tests for significant differences between the means of groups. An ANOVA test rejected the hypothesis that all of the mean widths for the groups were equal implying that at least one of the generations has a width significantly different from the other generations. Initial analysis showed that Generation 4 displayed significantly wider tunnel valleys (see Figure 5.34d, Table 6.1) compared to the other generations, however, a further ANOVA test omitting Generation 4 also concludes that at least one mean in another generation is also significantly different. Figure 6.2b shows a box plot of the widths in the seven tunnel valley generations outlined above. The box plot shows the median (fiftieth percentile) value as the centre line, the twenty fifth and seventy fifth percentiles as the lower and upper bounds of the box, the values 1½ times the
distance between the median and the twenty fifth and seventy fifth percentiles as the lower and upper adjacent values (t-bars), and any outliers (small circles). From Figure 6.2b it is apparent that Generation 4 shows not only the greatest mean width, but also the greatest dispersion of widths measured (plus a number of outliers). Generation 5 is seen to display a higher median width than Generation 4. This result is due to the separate measurement of each of the channels that makes up the anastomosing section of tv4b (see Figure 5.34d), which are generally smaller in width than the rest of Generation 4. If these reaches are discounted, Generation 4 displays the highest measures for median and mean width, as well as a smaller dispersion of widths.

Even after the removal of Generation 4 width data from the analysis, ANOVA testing finds that the remaining generations of tunnel valleys display significant differences in mean widths for generations. Pairwise ANOVA testing reveals that all of the generations display significantly different widths (i.e. the null hypothesis that the widths are the same is rejected) at a 95% confidence level, except for Generations 2 and 7, and Generations 3 and 3.5 which share similar values for width. It is therefore concluded that there is a relationship between generation and width within the northern study area. Specifically, Generation 4 tunnel valleys generally display widths between 2000 m and 7000 m, Generation 2, 6 and 7 tunnel valleys are relatively narrow (ca. 900 m), and Generation 3, 3.5 and 5 display intermediate widths (ca. 1200 - 1800 m). These results are most relevant to Generations 2 and 7 as all of the tunnel valleys in these generations were assigned on the basis of cross-cutting only and not morphological similarity which could lead to a self-satisfying relationship between generation and morphology (i.e. assigned to a generation partially by similarities in morphology, including width).

6.1.1.2 Lengths and Sinuosity

The analysis of tunnel valley length is limited to some extent by (a) that valleys frequently extend beyond the limits of the higher resolution 3D datasets and (b) by the dense numbers of cross-cutting tunnel valleys in the northern part of the study area. In areas where numerous generations of tunnel valleys have cross-cut one another (i.e. Dataset C, Figure 5.13), full lengths of valleys are often difficult to resolve, and tend to appear to terminate abruptly. However, truly abrupt initiation and termination is also a common characteristic of tunnel valleys, as shown in Figure 6.3, and so measurements of tunnel valley lengths are often only useful if they distinguish between tunnel valleys which appear to terminate beneath the margins of younger valleys (e.g. tvi, and tvj in
Dataset B, Figure 5.10), and those which can be seen clearly to extend beyond younger valleys, (e.g. for example, tv in Dataset B, Figure 5.10). Of the 57 tunnel valleys which can be separated into regional generations, at least 14 clearly extend beyond the boundaries of the study area to the north, making length measurements for these tunnel valleys a minimum. In the majority of other cases, tunnel valleys extend outwith Datasets A to M and into the regional dataset cnsmerge, where poor data quality makes accurate measurements of their lengths unreliable.

Most of the tunnel valleys within the northern study area display lengths greater than 12 km. Tunnel valley tv3a (Figure 5.35) is the longest tunnel valley within the northern study area, with a total reach of 117 km within the high resolution datasets. The regional dataset, cnsmerge, proved useful in assessing the full lengths of tunnel valleys where individual reach lengths extended outwith the boundaries of Datasets A – M. Where total tunnel valley reach length could be observed within good quality data, length measurements were made and are compared to generation as summarised in Table 6.2. Note that for many generations, observed lengths are a minimum value as the majority of tunnel valleys extend either beyond the limit of the study area 3D seismic data or into areas of unresolvable data. Where tunnel valleys could be traced into the regional dataset cnsmerge, these length measurements are included in the average.

<table>
<thead>
<tr>
<th>Regional Generation</th>
<th>Average Length within study extent (km)</th>
<th>Maximum Length (km)</th>
</tr>
</thead>
<tbody>
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<td>23</td>
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<tr>
<td>7</td>
<td>13</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 6.2 Average and maximum length measurements for tunnel valleys in the northern study area. Plus signs indicate the majority of tunnel valleys extend beyond limits of the study area.

Overall, Generation 2 and Generation 7 were more likely to start and stop within the study area and display characteristically ‘short’ tunnel valleys, with an average length of approximately 13.5 km, and abrupt start and end points (see the Generation 7 example from Dataset A in Figure 6.3). The remainder of the tunnel valley length measurements
are constrained by the extent and quality of the 3D seismic data they are imaged within but are generally at least tens of kilometres in length.

Sinuosity measurements were made for the buried tunnel valleys in order to approximate their planform parameters. Due to their formation by meltwater under pressure, tunnel valleys do not necessarily display the consistent relationship between gradient, length and sinuosity generally observed in subaerial fluvial channels (Knighton, 1998). However, tunnel valleys do display some elements of channel and valley morphologies such as high angle tributaries, bifurcation, and anabranching, and for these channel forms, sinuosity was found to be useful as a comparative measurement of meandering and directional change.

Sinuosity measurements were calculated for each tunnel valley in the northern study area by dividing the observed reach length by the straight line length \( \frac{L_{ti}}{L_s} \) (see Chapter 4.2.2.1) and were averaged within generations as included in Table 6.1. A histogram displaying sinuosity is shown in Figure 6.4a. Just over half of the tunnel valleys measured (59%) displayed sinuosities of less than 1.1, and are therefore described as “straight” in the fluvial classification system of Knighton (1998) and Charlton (2000). Generation 6 and Generation 3.5 display the highest average values (1.136 and 1.134 respectively) of sinuosity, but the individual tunnel valley with the highest level of sinuosity is in Generation 4 (tv4a in Figure 6.5a, sinuosity is 1.28). Analysis of variance (ANOVA) testing found evidence that there was a significant difference between the average sinuosities of the generations, although the resulting value (0.0456) is only just below the 95% confidence level. If Generation 6 is omitted from the analysis, the remaining generations do not show significant differences in sinuosity, and given their observed lengths and widths, are relatively straight compared to the majority of fluvial channels.

The results of the tests above indicate that sinuosity measured as \( \frac{L_{ti}}{L_s} \) (see Chapter 4.2.2.1) does not accurately describe the planform of the tunnel valleys observed in the northern half of the study area. For example, tv5a (Figure 6.4d) clearly shows significant changes in direction over tens of kilometres, yet its sinuosity measurement is less than that of tv3.5a (Figure 6.4c) due to a greater overall length. Similarly, tv3b (Figure 6.4b) displays a pronounced braiding in planform, but its sinuosity is 1.11, less
than that of tv3.5a (1.28). Overall, the sinuosity measurement is used to confirm the qualitative observation that tunnel valleys in Generations 2 and 7 tend towards straighter paths, while Generation 3.5 and 4 display significant southwards bending similar to that of Generation 5. The tunnel valleys in Generation 6 vary quite significantly in their direction and exhibit an overall higher measurement for sinuosity. In general, the analysis of weighted orientation measurements for each generation was found to better describe the morphology of the individual tunnel valleys.

6.1.1.3 Orientations

Weighted orientations for each tunnel valley within the seven generations of tunnel valleys in the northern half of the study area were measured as described in Chapter 4.2.2.3 (where 1 km equals one ‘unit’ of weighting) and are presented in Table 6.3. Weighting was used only as an indicator of directional strength and not length as length measurements were constrained by dataset extent. Note that all orientation measurements are bidirectional (axial) values as palaeoflow direction is unknown.

<table>
<thead>
<tr>
<th>Regional Generation</th>
<th>No. of measurements</th>
<th>Mean Orientation (axial)</th>
<th>Mean Length(r)</th>
<th>Circular Variance</th>
<th>Circular Standard Deviation</th>
<th>Rayleigh Test Probability (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>76</td>
<td>061</td>
<td>0.438</td>
<td>0.562</td>
<td>37°</td>
<td>4.70x10^-9</td>
</tr>
<tr>
<td>3</td>
<td>91</td>
<td>035</td>
<td>0.516</td>
<td>0.484</td>
<td>33°</td>
<td>2.87x10^-1</td>
</tr>
<tr>
<td>3.5</td>
<td>38</td>
<td>039</td>
<td>0.402</td>
<td>0.598</td>
<td>39°</td>
<td>0.002</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>063</td>
<td>0.493</td>
<td>0.507</td>
<td>34°</td>
<td>4.68x10^-4</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>169</td>
<td>0.371</td>
<td>0.629</td>
<td>40°</td>
<td>0.005</td>
</tr>
<tr>
<td>6</td>
<td>49</td>
<td>058</td>
<td>0.145</td>
<td>0.855</td>
<td>56°</td>
<td>0.357</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>091</td>
<td>0.247</td>
<td>0.753</td>
<td>48°</td>
<td>0.118</td>
</tr>
</tbody>
</table>

Table 6.3 Summary of weighted orientation measurements for Generations 2 – 7. Circular variance and circular standard deviation increase as data are more dispersed.

The mean orientation for each generation is the direction of the vector mean calculated for each group of tunnel valleys (Fisher 1993, Mardia and Jupp, 2000) and the mean length indicates the strength of this direction from 0 to 1, with 1 being the strongest. Circular variance provides a simple measure of dispersion around the mean resultant length, while circular standard deviation calculates dispersion around the mean resultant direction at a 95% confidence level. The results of the Rayleigh Probability test indicate whether a set of orientation measurements are evenly distributed (the null hypothesis), or if they display a preferred orientation (Fisher, 1993, p.70; Mardia and Jupp, 2000, p.94). In Table 6.3 the calculated probabilities (p) for the Rayleigh test which fall beneath the 5% significance level (0.05) do not fulfil the null hypothesis and so are
likely to contain a preferred orientation. Hence, the tunnel valleys in Generations 6 and 7 do not appear to display a preferred orientation. The results of the statistical analysis performed within this chapter are reliant on the assumption that the data collected in the orientation measurements populate a von Mises distribution, roughly equivalent to a normal distribution within linear data (see Chapter 4.2.2.3 and Fisher, 1993). The outcome of a Watson’s $U^2$ test, which provides a goodness of fit test against the von Mises distribution, resulted in a probability of less than 2.5% that the data did not follow the von Mises distribution (see Fisher, 1993, p.84). Figure 6.4b compares the orientation measurement (in blue) from the tunnel valleys in the northern study area to the von Mises distribution (black) and also shows a good fit to the distribution.

Figure 6.5 shows the weighted orientation measurements for each generation in the northern study area as a rose diagram where the number of measurements is given as $n$ and the frequency of the circle by $f$. Each rose diagram is divided into 40 sections, with each section equivalent to $9^\circ$. Generally, the majority of generations display a substantial NE-SW directional component, with 71% of orientation measurements (256 out of 358 total) between 000 and 090. However, there are significant differences in preferred orientations between generations; the results of the Rayleigh probability test (Table 6.3) indicate that each generations except Generations 6 and 7 shows evidence for a preferred tunnel valley orientation (i.e. Rayleigh Test resulted in a value of $< 0.05$, which rejects the null hypothesis that the average orientations are the same). Generations 6 and 7 also display the lowest mean length ($r < 0.3$), the highest circular variance ($> 0.7$), and the greatest values for circular standard deviation at 95% confidence level ($> 45$), which confirms their lack of directionality. It is worth bearing in mind that as a descriptive statistic, the above measurements provide not only an indication of the overall direction of the tunnel valleys within a generation, but also an idea of the variation within each generation. A large value for circular variation can be due to branching or changes in direction within an individual tunnel valley in the generation (e.g. tv5a in Generation 5, see Figure 6.5e) as well as individual tunnel valleys which display highly variable directions within a generation (e.g. Generation 6, Figure 5.34f). Similarly shaped tunnel valleys, for example, the ‘s-shaped’ tunnel valleys tv3.5a and tv5a (Figure 6.5), may lead to similar results when calculating summary statistics for orientation.
Overall, tunnel valleys in generations 2, 3, 3.5 and 4 appear to exhibit more pronounced preferred orientations than those in the younger generations 5, 6 and 7 (although Generation 5 only comprises two tunnel valleys and so any generalisation should be treated with caution). Generation 3 contains the strongest preferred orientation with a mean direction of 035 ± 33 and mean length (r) of 0.516 (see Figure 6.5b). Generation 4 also displays strong evidence for a preferred orientation, with a mean direction of 063 ± 34 and a mean length of 0.43 reflecting the south-west trending tunnel valleys in planform (Figure 6.5d). Generation 3.5, which appears to have been largely modified and re-occupied by Generation 4, displays a more north-south trend (axial direction is 039 ± 39) as a result of the tunnel valleys mapped in Datasets B and C which are later re-occupied by Generation 4 (see Figure 5.35). The tunnel valleys in Generation 2 display a preferred orientation around a mean direction of 061±37, as seen in Figure 6.5a. Generation 5, although it passes the Rayleigh Uniformity test, comprises only two tunnel valleys (Figure 6.5e), therefore increasing the values for circular variance and standard deviation. However, a comparison of Generation 5 and Generation 3.5 shows similar values in the analysis of orientation, perhaps due to the similarity in form between tv5a and tv3.5a, both of which are dominant tunnel valleys within their respective generations.

In order to fully compare the preferred orientations of the generations of tunnel valleys, a Watson-Williams F-test (Fisher, 1993, p. 126; Mardia and Jupp, 2000, p.129) was undertaken. The purpose of the test is similar to that of the ANOVA test used above with regard to tunnel valley widths, in that it compares the mean vectors from two or more sets of data (the generations of tunnel valleys in this case) to ascertain if they differ significantly (the null hypothesis states that they do not). Measurements for Generations 6 and 7 were removed from the data used to conduct the test, due to the results of initial analysis which showed little evidence for a preferred orientation. The outcome of a Watson-Williams F-test for all of the remaining generations resulted in a value of less than 1x10^{-12} (the minimum value possible), rejecting the null hypothesis that the mean orientations for all of the different generations is the same. Pairwise F-testing was then carried out to establish which generations could be distinguished from the others on the basis of orientation, and the results are presented in Table 6.4 where the values shown are the probability associated with the null hypothesis in the test. If the probability is less than the 0.05 significance level (5%) the null hypothesis is
rejected and it can be concluded that the mean orientations are significantly different between the pair of generations (asterisks indicate pairs which show no significant difference in Table 6.4).

Table 6.4 Results of a pairwise Watson-Williams F-test showing the probabilities associated with the null hypothesis that the mean orientations are equal for each pair. Asterisks indicate pairs with no significant difference in orientation.

<table>
<thead>
<tr>
<th></th>
<th>Gen 2</th>
<th>Gen 3</th>
<th>Gen 3.5</th>
<th>Gen 4</th>
<th>Gen 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen 2</td>
<td>-------------</td>
<td>9.70x10^-6</td>
<td>0.007</td>
<td>*0.88</td>
<td>1.27x10^-11</td>
</tr>
<tr>
<td>Gen 3</td>
<td>*0.573</td>
<td>3.71x10^-6</td>
<td>0.017</td>
<td>5.59x10^-6</td>
<td>1.38x10^-97</td>
</tr>
<tr>
<td>Gen 3.5</td>
<td>----</td>
<td>----</td>
<td>1.27x10^-11</td>
<td>1.79x10^-99</td>
<td>----</td>
</tr>
<tr>
<td>Gen 4</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>1.38x10^-97</td>
<td>----</td>
</tr>
<tr>
<td>Gen 5</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>5.59x10^-6</td>
<td>----</td>
</tr>
</tbody>
</table>

The results of the test indicate that the majority of the generations display significantly different mean orientations, particularly Generation 5, which can be distinguished from all others on the basis of orientation. Surprisingly, Generations 3.5 and 4 do not share a preferred orientation; given that Generation 4 extensively re-occupies the tunnel valleys of Generation 3.5 along much of their reach (see Chapter 5). However, the resultant test value of 0.017 is significantly greater than for other comparisons, and the generations could be considered to share a similar orientation if the chosen significance level was reduced to 1%. Generations 2 and 4 and Generations 3.5 and 3 show no significant difference in mean orientation (i.e. the null hypothesis is accepted), whether the significance level is set at 1% or 5%. The average mean orientation calculated for Generations 2 and 4 is 0.062, and for Generations 3.5 and 3 is 0.036. The maximum difference between mean orientations for generations is between Generation 2 and Generation 5. Excluding Generation 5, the largest difference between mean orientations is between Generations 2 and 3, although this may be influenced by the large number of tunnel valleys in the northern study that are assigned to Generation 2, which necessarily result in a stronger mean resultant length.

Overall, the buried tunnel valleys in Generations 2 to 7 exhibit significant differences in their orientation with respect to generation, although all generally follow a NE-SW trend. Some groupings can be made, with Generations 2 and 4 and 7 displaying a straightforward ENE-WSW component close to 0.065, while Generations 3 and 3.5 tend towards a NNE-SSW orientation (c. 0.035).
6.1.1.4 Depths and Basal Relief

Basal depths for individual tunnel valleys were found to vary along thalweg for the majority of the tunnel valleys in the northern study area, as is common for features interpreted as tunnel valleys (see Chapter 2.3). Figure 6.6a provides a representative example showing distance (km) versus TWTT at base of tunnel valley for part of the reach of tv5a within Datasets A and B (from a to a' in Figure 6.5e). Measurement errors are a maximum of ± 12 ms TWTT. Figure 6.6b shows the same data with TWTT converted to depth using a sediment velocity of 1750 ms⁻¹ and with seabed at 180 ms TWTT. Resultant error measurements for depth converted results are estimated at ± 11 m as described in Chapter 4.2.2.4. Using these parameters, the internal depth of the tunnel valley can be seen to vary by up to 70 m (± 11 m) over a distance of 12 km. Figure 6.6c shows the internal depth of the valley (i.e. from base to shoulder) along its length, taking the deepest part of the tunnel valley as 0 and using the same sediment velocity (1750 ms⁻¹) and error bars (± 11 m) as above. This last measure was found to be most appropriate when comparing depths along reach of the tunnel valleys as it avoids the problems associated with time shifts between datasets (see Chapter 4.1.3 for more information) and instead directly compares the internal dimensions of the tunnel valleys regardless of depth below seabed. Figure 6.7 shows the results of comparing basal depths along reach for a number of tunnel valleys from datasets within the northern study area which reflect the tendency for all of the measured tunnel valleys to display an undulating thalweg. Figure 6.8 illustrates the varying relief in basal depth for tv3a as imaged in seismic profile in Dataset A (location a-a’ in Figure 6.5b).

Width to depth ratios were calculated for each generation of tunnel valleys based on average values of width and maximum values for depth measured from individual valleys in each generation (see Table 6.1). As it was not possible to accurately measure the depths of all the tunnel valleys in the northern study area (due to data quality issues, see Chapter 4.1.3) the resulting width to depth measurements are representative rather than comprehensive. However, they do reflect the general width to depth trends for the generations in the northern study area, with the wide, shallow tunnel valleys in Generation 4 displaying significantly higher w:d values (greater than 45) and Generation 2 tunnel valleys exhibiting narrower, deeper forms, with average w:d values of 9. The remaining generations generally displayed width to depth values of 15 – 20 and it was not possible to distinguish these generations on the basis of width versus
depth ratios. The majority of buried tunnel valleys in the northern study area displayed average internal (from base to shoulder) depths between 80 and 200 m.

6.1.1.5 Other Morphological Features

Anastomosing and branching reaches are observed within tunnel valleys in Generations 3, 4, 5 and 6. Tunnel valley tv3b in Generation 3 displays a striking anastomosing pattern along its entire length, with a number of ‘islands’ between the two main channels which make up the tunnel valley (see Figure 6.9a). Tunnel valley tv3a also contains an ‘island’ where it is mapped in Dataset A (see tve in Figure 5.5). The large tunnel valley tv4a shows anastomosing reaches with a maximum of three branches imaged in the regional dataset cnsmerge and also in Dataset F (see tunnel valleys tvj and tvk in Figure 5.20). Tunnel valley tv5a displays a number of ‘islands’ in Datasets A and C (e.g. see tvh in Figure 5.10).

Terracing along the valley walls of tunnel valleys is also relatively common (see Figure 6.9b). Larger terraces sometimes display a curvilinear form which can be compared to relict meander bends in fluvial systems, and may imply straightening of the channel over time, or subaerial fluvial modification by meandering channels. An interesting morphological feature observed within tunnel valleys with anastomosing reaches is the tendency for one branch of the bifurcating channel to display a shallower cross-sectional morphology as in Figure 6.9c. Analogous features in subaerial channels are usually the result of bifurcation due to the initiation of a secondary channel during flood events. The secondary channels are subsequently abandoned when discharge decreases. If meltwater input was variable during tunnel valley formation, this process could be responsible for the relatively isolated anabranching reaches of individual tunnel valleys, implying bifurcation during high discharge episodes.

Some degree of branching (without rejoining) is observed within individual tunnel valleys within all generations apart from Generation 7. High angle branching (c. 45° - 90°) can be used to indicate the presence of ‘hanging valley’ relationships, where tributary tunnel valleys are seen to feed into larger tunnel valleys from above the main channel. An example of this can be seen within Dataset A where a relatively shallow tributary channel to tvh (see Figure 5.5 for location) joins the main branch at an angle of approximately 80° as illustrated in Figure 6.10.
Little evidence was found for a link between tunnel valley wall steepness and generation, with values across all generations ranging from 5° up to 40° (Figure 6.11, measured as described in Chapter 4.1.1.2). Asymmetry between valley wall steepness measurements (e.g. a difference of greater than 5°) was a common feature, but was not associated with any particular generation or orientation. Occasionally, the steepest tunnel valley flanks were observed on the outside of bends, as in fluvial systems (see the example from tv5a in Figure 6.11e and tvh in Figure 6.10b) but no consistent relationship was established between meander direction and steepness in cross-profile that could assist in estimating a palaeoflow direction. Most of the tunnel valleys displayed generally u-shaped cross-profiles, with a flat base and relatively steep walls, although Generation 2 tended to display narrower, v-shaped profiles, related to their overall lower width to depth values (see Figure 6.11a).

Compared to the seabed tunnel valleys studied in Chapter 8 of this work, the generations of buried valleys in the northern study area display little evidence for regular spacing, with the possible exception of Generations 2 and 3, which show evidence for tunnel valley incision at approximately 10 km and 15 km intervals respectively. However, the limited number of tunnel valleys observed within each generation precludes further analysis, and it is considered here that a morphological characteristic of the buried tunnel valleys is that they are not regularly spaced.

6.1.1.6 Generation 1 – tunnel valley tv1a
Tunnel valley tv1a (see Figure 5.35 for location) is unique within the northern study area as it appears to incise from a lower stratigraphic level than the surrounding tunnel valleys (i.e. see Figure 5.27). The morphological characteristics of tv1a are considered to be similar enough to those of the surrounding tunnel valleys to classify it as a tunnel valley with ease. In particular, tv1a displays the irregular base and u-shaped cross section common to younger tunnel valleys (see Figure 6.12, 6.13). The tunnel valley, which is observed in Datasets H and I, and also in the regional dataset cnsmerge, is therefore considered to be the oldest tunnel valley in the northern study area and is assigned to Generation 1 in the regional framework outlined in Chapter 5.

Tunnel valley tv1a is reasonably well-imaged in timeslice in both Dataset H and Dataset I (see Figure 6.12a,b), although its cross-sectional morphology is more difficult to establish in Dataset I due to the influence of cross-cutting tunnel valleys from younger
generations, and the relatively poor data quality in the western part of Dataset I (see Figure 6.12c, d).

<table>
<thead>
<tr>
<th>Regional Generation</th>
<th>Average Width (m)</th>
<th>Maximum Width (m)</th>
<th>Minimum Width (m)</th>
<th>Sinuosity</th>
<th>width:depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1226</td>
<td>1576</td>
<td>994</td>
<td>1.16</td>
<td>24</td>
</tr>
</tbody>
</table>

*Table 6.5 Summary of morphological measurements for tunnel valley tv1a in Generation 1.*

The average width of the tunnel valley is similar to that of Generations 3, 3.5 and 5 in the regional generational framework. However, internal depths for tv1a (from base to shoulder) are slightly shallower than those observed within the younger generations, with average depth values of 30 – 60 m (e.g. see Figure 6.12c). As a result, width to depth values for tv1a are relatively high. Valley wall steepness was found to vary between 6° and 11°. Like the valleys in other generations, tunnel valley tv1a has a characteristically undulating base (see Figure 6.12e). Measurement error is in the region of ± 12 m for the depth of the tunnel valley base, so the resulting record of variation in basal depth approaches the limit of vertical resolution in the datasets (e.g. ca. 8 – 10 m).

The result of orientation measurements carried out for tv1a shows that the tunnel valley displays a preferred orientation (Rayleigh test p = 0.0004) and that the weighted mean orientation is 040 ± 24. A comparison to the younger generations in the northern study area using the Watson-Williams F-test (see Chapter 6.1.1.4) indicates that tv1a displays a similar preferred orientation to the tunnel valleys within Generation 3 and Generation 3.5 (i.e. the null hypothesis is valid). The mean orientation for Generations 1, 3 and 3.5 is then calculated at 035 (NE-SW), which differs significantly to the mean orientation of Generations 2, 4, 6 and 7.

In planform, tv1a displays a curvilinear form, resulting in its relatively high sinuosity value of 1.16 (see Figure 6.12, 6.13). It contains two conspicuous tributary branches which join the main part of the tunnel valley at similar angles (approximately 40°) and trend NNW-SSE (see Figure 6.12a,b, 6.13). At the southern junction (location A in Figure 6.12a, 6.13) the tributary rises upwards and splits into three channels over a distance of c. 5km before joining the main tunnel valley in what is likely to be an example of the hanging valley relationship described in the previous section.
6.2 Southern Study Area

In the southern part of the study area (defined here as south of 57°30'N) morphological measurements of tunnel valleys were obtained from the 3D seismic reflection Dataset M (see Figure 6.1a for location, Figure 6.1b for dataset extent and bin size).

6.2.1 Results - Dataset M

As described in Chapter 5, the tunnel valleys within Dataset M can be split into three cross-cutting generations, termed Generation 1M, 2M and 3M to distinguish them from the generations in the northern study area. Morphological analysis of the tunnel valleys within the generations was carried out as described in Chapter 4.2.2.1 and the results are presented in Table 6.6.

<table>
<thead>
<tr>
<th>Dataset generation</th>
<th>No. of measurements</th>
<th>Average Width (m)</th>
<th>Maximum Width (m)</th>
<th>Minimum Width (m)</th>
<th>Average Sinuosity</th>
<th>Average Width:Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation 1M</td>
<td>27</td>
<td>2072</td>
<td>3046</td>
<td>1115</td>
<td>1.04</td>
<td>n/a</td>
</tr>
<tr>
<td>Generation 2M</td>
<td>31</td>
<td>1291</td>
<td>1589</td>
<td>643</td>
<td>1.05</td>
<td>9</td>
</tr>
<tr>
<td>Generation 3M</td>
<td>44</td>
<td>1134</td>
<td>1662</td>
<td>670</td>
<td>1.06</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 6.6 Summary of morphological measurements for the three generations of tunnel valleys in Dataset M.

The average width for all of the tunnel valleys in Dataset M is 1499 m. ANOVA testing indicates that there is a significant difference in widths between Generation 1M and Generations 2M and 3M, with the former displaying widths in the range of 2000 m (based on measurements from only three tunnel valleys, see Figure 5.32) and the latter widths between 1100 and 1300 m. Average sinuosities for the three observed generations do not appear to vary significantly, but it is noted that Generations 2M and 3M are characterised by extensive anastomosing reaches, and some bifurcation, as shown in Figure 6.13b. A pronounced seabed multiple and poor vertical resolution in the vicinity of the Generation 1M tunnel valleys in Dataset M meant that average depths could not be established. Estimated internal depths for Generation 1M range from about 250 m to 300 m, making the w:d ratio for these older tunnel valleys in the region of 13. Generation 3M in Dataset M is dominated by the large anastomosing system of tunnel valleys identified as tvk in Figure 5.31. This system is of a similar width to the tunnel valleys in Generation 2M, but are generally shallower in cross-section, widening towards their top and resulting in an overall greater w:d ratio for the youngest generation. Figure 6.14 shows the tunnel valleys within Dataset M as imaged in timeslice and representative cross-sectional morphologies for Generation 3M. Valley
wall steepness for the tunnel valleys in Dataset M are similar to those in the northern study area, ranging from 5° up to a maximum of 35° (Figure 6.14c). The majority of tunnel valleys in Dataset M also exhibited the undulating long profile characteristic of the buried tunnel valleys in the northern study area, as seen in Figure 6.14d.

Many of the tunnel valleys in Dataset M can clearly be seen extending outwith the dataset boundaries and are traced into the regional dataset cnsmmerge. Tunnel valley tvb, which forms part of Generation 1M, appears to have a minimum total reach length of c. 80 km. Tunnel valley tvh also appears to form part of a larger tunnel valley which has a total length of more than 65 km. Relatively poor data quality in the regional dataset cnsmmerge surrounding Dataset M precludes more detailed length measurements, but it is considered that the above length measurements are representative for the study area proximal to Dataset M.

The orientations for each generation of tunnel valleys are presented in Table 6.7. The resulting axial values were found to approximate a von Mises distribution.

<table>
<thead>
<tr>
<th>Dataset M Generation</th>
<th>No. of measurements</th>
<th>Mean orientation</th>
<th>Mean Length (r)</th>
<th>Circular Variance</th>
<th>Circular Standard Deviation</th>
<th>Rayleigh Test Probability (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>067</td>
<td>0.584</td>
<td>0.416</td>
<td>30°</td>
<td>0.003</td>
</tr>
<tr>
<td>2</td>
<td>34</td>
<td>113</td>
<td>0.544</td>
<td>0.456</td>
<td>32°</td>
<td>5.55x10^-5</td>
</tr>
<tr>
<td>3</td>
<td>85</td>
<td>112</td>
<td>0.595</td>
<td>0.405</td>
<td>29°</td>
<td>&lt; 1x10^-12</td>
</tr>
</tbody>
</table>

Table 6.7 Summary of orientation measurements for Dataset M tunnel valleys.

The results of a Rayleigh test indicate that each generation displays a preferred orientation (i.e. p < 0.05 at a 95% significance level). Circular variance and standard deviation for each generation are relatively low compared to the buried generations of tunnel valleys in the northern study area, indicating a more pronounced preferred orientation for the tunnel valleys in Dataset M. A comparison of orientations between generations within this dataset (using the Watson-Williams F-test described in Chapter 4.2.2.3 and 6.1.1.4) indicates a strong difference between Generation 1M and Generations 2M and 3M, with Generations 2M and 3M displaying no significant difference between their average orientations. The mean preferred orientation for Generations 2M and 3M is then calculated as 113 ± 32 (approximately ESE-WNW) while Generation 1M displays a preferred orientation of 067 ± 30 (approximately ENE-
WSE). Figure 6.15 illustrates the weighted orientation for each of the three generations of tunnel valleys in Dataset M.

The Watson-Williams F-test was also carried out to establish whether the tunnel valleys in Dataset M displayed a significantly different mean orientation than those in the northern study area. The results demonstrated that Generation 1M in Dataset M, and Generations 2 and 4 in the northern study area share a similar mean orientation value calculated at 063 (ENE-WSW), but that Generations 2M and 3M display a significantly different mean orientation (ESE-WNW) compared to all of the generations of tunnel valleys in the northern study area.

6.3 Discussion

6.3.1 Width, Length, Depth and Planform
Tunnel valleys in all datasets display an apparent relationship between width and generation (see summary in Table 6.8). In the northern study area three groupings emerge: Generations 2 and 6 display widths of less than 1000 m, Generations 1, 3, 3.5, 5 and 7 have average widths between 1000 m and 1800 m and Generation 4 is characterised by significantly wider tunnel valleys up to 7500 m in width. To the south, tunnel valley width in Dataset M range between 1100m and 2100 m, with Generation 1M (the oldest) displaying the widest tunnel valleys, and Generations 2M and 3M displaying similar widths of around 1200 m. Generally, the average width of a tunnel valley in Dataset M is greater than that observed in the northern study area. However, measurements of width for tunnel valleys observed in the regional cnsmerge dataset do not reveal any significant difference in average widths between the northern and southern parts of the study area.
Table 6.8 Summary of morphological measurements for all tunnel valleys studied in Datasets A – M. Mean orientation values with an asterisk indicate the generation displays no significant preferred preferred orientation.

<table>
<thead>
<tr>
<th>Generation</th>
<th>Average Width (m)</th>
<th>Average Sinuosity</th>
<th>Width: Depth (typical)</th>
<th>Mean Orientation ± Standard Deviation</th>
<th>Planform complexity?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1266</td>
<td>1.16</td>
<td>24</td>
<td>040 ± 37</td>
<td>Some</td>
</tr>
<tr>
<td>2</td>
<td>723</td>
<td>1.055</td>
<td>9</td>
<td>061 ± 37</td>
<td>Minimal</td>
</tr>
<tr>
<td>3</td>
<td>1150</td>
<td>1.097</td>
<td>16</td>
<td>035 ± 33</td>
<td>Yes</td>
</tr>
<tr>
<td>3.5</td>
<td>1437</td>
<td>1.134</td>
<td>17</td>
<td>039 ± 39</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>2657</td>
<td>1.105</td>
<td>&gt;45</td>
<td>063 ± 34</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>1800</td>
<td>1.053</td>
<td>19</td>
<td>169 ± 40</td>
<td>Some</td>
</tr>
<tr>
<td>6</td>
<td>944</td>
<td>1.136</td>
<td>15</td>
<td>*058 ± 56</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>1047</td>
<td>1.106</td>
<td>15</td>
<td>*091 ± 48</td>
<td>Minimal</td>
</tr>
<tr>
<td>1M</td>
<td>2072</td>
<td>1.04</td>
<td>n/a</td>
<td>067± 30</td>
<td>Minimal</td>
</tr>
<tr>
<td>2M</td>
<td>1291</td>
<td>1.05</td>
<td>9</td>
<td>113±32</td>
<td>Yes</td>
</tr>
<tr>
<td>3M</td>
<td>1134</td>
<td>1.06</td>
<td>13</td>
<td>112±29</td>
<td>Some</td>
</tr>
</tbody>
</table>

In some cases the cross-sectional morphology of the tunnel valleys is characteristic of a generation. Specifically, the tunnel valleys in Generation 4 in the northern study area display particularly high width to depth ratios (> 45) and display broad, shallow morphologies which are seen to re-occupy younger generations (see Figure 5.39). Generation 2 tunnel valleys are often narrow and deep, with lower than average width to depth measurements (c. 9). The oldest tunnel valley in the study area, tv1a, is relatively shallow, with internal depths of less than 60 m, compared to average depths of 80 – 200 m, resulting in higher than average width to depth measurements of 24. The remainder of the tunnel valleys in the northern study area and Dataset M do not exhibit any significant variations between width to depth ratios and generation or location, with average width to depth ratios values falling between 12 and 20, in line with the compilation of Gibling (2006). In comparison, Kristensen et al. ’s (2007) study of buried tunnel valleys in the southern North Sea revealed width to depth ratios of between 6 and 10, similar to those observed in Generation 2 of this work, which are overall deeper and narrower than some of the younger generations.

Valley wall steepness for all tunnel valleys was found to range between 5° and 40°, with little evidence for a link to generation or location. The majority of tunnel valleys were broadly u-shaped in profile, although Generation 2 tunnel valleys tend towards a more v-shaped cross-section (i.e. see Figure 6.11a). Asymmetry between tunnel valley flanks
was a common feature, but extensive analysis found no consistent relationship could be made between aspect and steepness such as that suggested by Wingfield (1991). In some cases, a clear link could be made between asymmetry and planform, with the steeper channel flank observed on the inside of a bend as in fluvial systems (e.g. for tv3a in Dataset A, Figure 6.11) but again this was not observed to occur regularly or within particular generations.

In terms of planform geometry, Generations 2 and 7 in the north of the area show little evidence for complexity in planform (i.e. anastomosing reaches or meander-type bending) and therefore record a relatively low value for sinuosity. Also, although the tunnel valleys studied in Dataset M show a relatively high value for sinuosity (due to local meandering and an extensive anastomosing section in Generation 3M), their directionality is more pronounced and individual tunnel valleys show less meandering and bending over a larger scale (e.g. tens of kilometres) than those tunnel valleys in the northern part of the study area.

Terracing and evidence for 'cut-off bends' are fairly common morphological features within all of the tunnel valleys in the study area (see Figure 6.9), and appear a common characteristic of the central north sea tunnel valleys systems regardless of the generation in which the valley occurs. Wider tunnel valleys (> 1200 m) were more likely to display terrace-type morphologies on one or both flanks, but this could just be a reflection of ease of identifying terraces on larger valley systems.

Although anastomosing reaches of tunnel valleys are not especially common throughout the study area, they do occur locally in several generations in the north (Generations 3, 4, 5 and 6), and dominate Generation 3M in Dataset M (southern study area). Anastomosing reaches are also common in the small (11 x 7km) dataset located 15 km to the east of dataset E (Lonergan et al., 2006, see Figure 5.38 for location) One factor in the identification of anastomosing systems may be lateral resolution - the datasets used in Lonergan’s (2006) work and Dataset M both have bin sizes (and therefore effective lateral resolution) of 12.5 x 12.5 metres, compared to a minimum spacing of 25 x 25 metres for datasets in the northern study area. However, the fact that tv3b is clearly imaged inDatasets B, C and F (25 x 25 m), and the anastomosing reach of tv1a is pronounced in Dataset H (with a bin spacing of 50 x 50 m; Figure 6.12) suggests this
may not be the case. There thus appears to be no link between anastomosing complexity and tunnel valley generation or spatial location. The formation of complex anastomosing-braided patterns appears to be a characteristic of the North Sea tunnel valley systems although limited in number to local areas in any one generation of tunnel valley.

Analysis of tunnel valley lengths is limited by data extent, but the majority of tunnel valleys appear to display lengths greater than 30 km. Many tunnel valleys can be seen to extend for more than 100 km in the dataset cnsmmerge (i.e. see Figure 6.1) but are not associated with any other particular morphologies.

Overall, this work finds some evidence for variation of tunnel valley morphologies between generations and spatially within the central North Sea. For example generation 2 tunnel valleys exhibit consistently narrow, deep, v-shaped and relatively straight morphologies in comparison to the younger generations, and display little evidence for planform complexity (e.g. bifurcation or high sinuosities). Generation 4, conversely, demonstrates a wide, relatively shallow morphology, and a significant anastomosing reach in tv4b. Length, valley wall symmetry and planform geometry are broadly similar for all tunnel valley generations and compare to other works in the region (Lonergan et al., 2006; Kristensen et al., 2007). Overall, the results of the morphological analysis demonstrates that the geometry of tunnel valleys in the central North Sea varies significantly over tens of kilometres and within a single generation (e.g. see the difference in form between tv3a and tv3b in Figure 5.35) but there are also morphological characteristics that are common to the majority of the tunnel valley systems regardless of their age, for example, undulating long profiles, abrupt initiation and termination, steep valley sides, tributary valleys at higher levels (hanging valleys), and terracing in broad reaches.

6.3.2 Orientation

Tunnel valley orientations do, however, vary significantly between generations from north to south through the study area (see Table 6.4; Figure 6.5; Figure 6.8). Figure 6.16 illustrates the differences in orientation between Generations 1 through 7 in the northern study area (weighted orientations shown in Figure 6.16a,b) and Generations 1M, 2M and 3M (Figure 6.16c,d) in Dataset M in the south. Figure 6.17 shows the
orientation measurements as measured from tunnel valleys imaged in Datasets A-H in the northern study area in more detail.

In the northern part of the study area (north of 57°30'N, Figure 6.17) the mean resultant direction for all tunnel valleys is 031 (c. NE-SW). In the southern part of the study area, the mean resultant direction is significantly different (at a 99% confidence level) at 152 (c. SE-NW), as seen in Figure 6.16d. A Rayleigh test for both sets of orientation measurements (including measurements from the cnsmerge dataset) reveals that the tunnel valleys in the southern part of the study area display a strongly preferred orientation (e.g. $p = 2 \times 10^{-4}$). Tunnel valley orientations in the north are more evenly distributed and do not display a preferred orientation when considered as a whole (a Rayleigh test returns a value of $p = 0.1$).

The result of orientation measurements become more pronounced when the tunnel valleys are considered in the age framework established in Chapter 5. In the northern study area, although all of the generations display some NE-SW component, the generations can be separated into three broad groupings based on orientation. Tunnel valleys in generations 2 and 4 trend more ENE-WSW (i.e. mean orientation approximates 065) while those in generations 1, 3, 3.5 and 5 show a stronger NNE-SSW component (i.e. mean orientation is 035). Generations 6 and 7 contain tunnel valleys of widely varying orientation and as such cannot be considered to display a significant preferred orientation, although calculation of their mean orientation yields values similar to those of Generation 1, 2 and 4 (c. 065). Tunnel valleys in generation 1M in Dataset M also share a similar mean resultant orientation to those of Generations 1, 2, and 4 in the northern study area. Generations 2M and 3M, in contrast, contain tunnel valleys with a strong NW-SE trend, and a mean resultant orientation of 113. Measurements made in the southern half of the study area from the regional cnsmerge dataset also show a strong NW-SE orientation. Figure 6.16 summarises these findings for the regional study area, while Figure 6.17 displays the orientation measurements for the individual generations of tunnel valleys in the northern study area in more detail.

In summary, there is a significant change in orientation and spacing of tunnel valleys from north to south within the study area. In the northern study area, the palimpsest of tunnel valley generations tend to trend approximately NE-SW, but do not display a
particularly strong preferred orientation or pattern of distribution. To the south, the buried tunnel valleys display a strongly preferred NW-SE orientation, and exhibit more regular spacing. Some important generalisations regarding the formation of the tunnel valleys with respect to Pleistocene ice extent can be considered in light of these regional changes in orientation and spacing.

In the northern part of the study area, the large scatter of orientations observed and the lack of regular tunnel valley spacing implies that, even within individual generations, tunnel valley incision was not clearly related to a well-defined, static ice-sheet margin, where tunnel valley incision would be largely controlled by hydrostatic head influenced by the position and slope of the ice-sheet margin. In general, tunnel valleys associated with drainage headwards from an ice margin are considered to display regularity in spacing and direction (e.g. Praeg, 1996), as is observed for the tunnel valleys imaged in the southern part of this work (i.e. see Figure 6.16). It is considered here that the multiple generations of tunnel valleys observed in the northern part of the study area formed towards the centre of the Pleistocene ice sheets, where drainage was dominated by local accumulation centres and possibly by dynamic ice streaming processes. To the south of the study area, the buried tunnel valleys reflect increased dominance by a relatively proximal ice margin which must have existed during a number of the Pleistocene glaciations in the region. Chapter 9 of this work further considers the evidence from this work with respect to the relationship between buried tunnel valleys Pleistocene ice sheet dynamics and extent.

6.3.3 Morphology and Formation

This chapter has focussed on describing the main geometrical features of the tunnel valleys within the separate generations identified in Chapter 5. The results of the morphological measurements made above indicate a variety of form for the tunnel valleys both within and independent of generation and location.

The majority of the tunnel valleys studied display evidence for a significantly undulating basal profile (Figures 6.6, 6.7, 6.8), a feature commonly used in other studies to indicate formation by pressurised meltwater (see Chapter 2; Lonergan et al., 2006; Kristensen et al., 2007). The results of this extensive analysis of some 180 buried tunnel valleys further confirms the dominant mode of formation of the buried North Sea tunnel valleys as being subglacial.
Generation 4 tunnel valleys are seen to re-occupy an older generation of tunnel valleys in the northern study area (see Figure 5.34), and display a very high width to depth ratio (see Table 6.1, Figure 5.39). Large tunnel valley widths may be envisaged as resulting from the influence of: an internally migrating channel during tunnel valley formation; glacial or subaerial modification post-formation; ice sheet configuration; or a combination of all three factors. A tunnel valley which is incised over time by a smaller channel within its reach may be more likely to display a wider form due to lateral migration of the internal channel in its top part. This method of formation for tunnel valleys has been discussed by Praeg (1996, 2003), Huuse and Lykke Andersen (2000), and Jørgensen and Sanderson (2006) amongst others (see Chapter 2.2.3) and is suggested that it is associated with episodic discharge of surficial meltwater due to seasonal melting (van Dijke and Veldkamp, 1996). To result in the morphology observed in the tunnel valleys in Generation 4, the channel would either: (a) be required to remain active during fill, as the widening is most pronounced towards the top of the tunnel valley or (b) have straightened over time as suggested by Lonergan et al., (2006, see Figure 8, p.901). The former scenario can be envisaged if cyclical melting was a factor, as deposition would partially fill the tunnel valleys during times of reduced surface melting (when any internal channels were not active) and tunnel valley excavation would continue at a higher level when surficial melting was sufficient to support the renewed activation of the internal channel. Another factor which would result in relatively wide, shallow tunnel valleys relates to direct glacial erosion where glacial ice could modify the upper parts of tunnel valleys originally formed subglacially, as discussed, for example, by Huuse and Lykke-Andersen (2000). Both modes of formation result could result in an end morphology that displays the characteristics of those found in Generation 4, as shown in Figure 6.18a, and imply that the formation of wide tunnel valleys is a result of prolonged ice cover driving a significant subglacial drainage system, and/or direct glacial erosion. Subaerial modification of a tunnel valley after its formation would also result in a widening of the original channel due to lateral migration of internal fluvial channels, but requires the original tunnel valley to be preserved in the landscape for some time between renewed ice cover and for the modification to occur as the tunnel valley is filled, for the same reasons as above.
Another explanation for a generation of relatively wide tunnel valleys might be related to the effect of ice sheet thickness and duration on tunnel valley formation. The reduced hydrostatic pressure beneath relatively thin ice towards the centre of an ice sheet could result in wider tunnel valleys due to lower water pressures which enabled lateral freedom for tunnel valleys with the result that they are able to migrate over time and therefore widen. Similarly, in tunnel valleys formed some distance from the ice margin, hydrostatic gradient is likely to be relatively gentle, possibly allowing channels to widen and meander beneath the ice. However, a lack of knowledge regarding the thickness of the Pleistocene ice cover in the central North Sea, and the possible influence of local ice domes and/or ice streams precludes more detailed consideration.

Thinning ice sheets could also be associated with high levels of surficial melting leading to an increase in meltwater influx to the subglacial channel system and necessitating an increase in their capacity, thus resulting in widening. However, hydrologically, wide, shallow channels are less efficient conduits than deep, narrower channels (Knighton, 1998) and so it is unlikely that a sustained increase in meltwater influx would lead to the formation of wide, shallow tunnel valleys. Alternatively, occasional increases in meltwater influx could raise porewater pressures and result in liquefaction of the subglacial sediment near to the glacier bed, reducing bank cohesiveness and encouraging lateral migration towards the top of a tunnel valley.

Conversely, Generation 2 tunnel valleys display relatively narrow, deep, v-shaped cross-sectional morphologies more similar in form to high relief fluvial channels (albeit at depths of at least one order of magnitude greater than subaerial channels). Generation 2 tunnel valleys generally show little planform complexity along their reach, with only one tunnel valley in the generation (tvd in Dataset F) displaying bifurcation. A lack of terracing, cut-off bends or sinuous reaches within the generation implies a lack of post formation modification, and it is unlikely that the v-shaped morphologies were created by in-valley lateral erosion as suggested for Generation 4. Conditions which favour the formation of deep, narrow tunnel valleys may include those which encourage increased cohesiveness (for example, increased clay content) in subglacial sediment and rapid tunnel valley infilling soon after their excavation. Formation beneath a rapidly melting ice sheet with a well-defined margin could sustain these conditions, with tunnel valleys forming in response to an increased meltwater influx. If the tunnel valleys formed
rapidly and were able to drain the meltwater efficiently, Darcian flow in the surrounding sediments would be reduced, resulting in low porewater pressure and relatively high levels of cohesiveness which would support steep-walled tunnel valleys, further enhancing the efficiency of flow.

Generation 3.5 tunnel valleys are defined by their re-occupation and therefore must have been present in the landscape after their initial formation. This is in contrast to the majority of tunnel valley generations in the northern study area which can be seen to cross-cut older generations of tunnel valleys without being deflected or captured (e.g. see Figure 5.39 where tvo clearly cross-cuts tvm (Generation 4) which follows the path of tvi and tvj). It can therefore be concluded that Generation 3.5 tunnel valleys were completely infilled after their formation, in which case, the ice sheet associated with the Generation 4 tunnel valleys must have readvanced over the area relatively quickly, or that their formation was a result of different subglacial conditions which did not lead to rapid filling. Considering that the majority of the other tunnel valleys do not display evidence for substantial re-occupation, and do not display significantly different morphologies to Generation 3.5, it is considered here more likely that the re-occupation reflects timing rather than ice sheet conditions. In this case, it is likely that the ice sheet which initiated the formation of the Generation 3.5 tunnel valleys also formed the Generation 4 tunnel valleys which re-occupied them. In such a scenario, it could be envisaged that the tunnel valleys of Generation 3.5 were originally formed beneath an ice sheet with a similar configuration to that of Generation 3 (due to their similarity in orientation, see Chapter 9 for more on ice sheet configurations) which then retreated, leaving the tunnel valleys in Generation 3 only partially filled. The ice sheet then readvanced and re-used the tunnel valleys in Generation 3.5 as part of its subglacial drainage system before thinning to produce the characteristically wide tunnel valleys of Generation 4. It could be the case that the presence of Generation 3.5 as a pre-existing drainage network enhanced rapid thinning of the ice during the readvance by reducing the need to create new drainage pathways and therefore played a part in creating the wide shallow morphologies which characterise Generation 4. Figure 6.18b illustrates this formation sequence.

These observations suggest some differences in tunnel valley morphology are influenced by formation processes that vary depending on glaciological conditions at
the ice-sheet bed, and by proximity to ice-sheet margin. Duration of ice cover and thinning and readvance may also be directly linked to tunnel valley form.

6.4 Conclusions

The remainder of the conclusions for this chapter are summarised below. Detailed morphological measurements including data on width, length, basal relief, sinuosity, valley wall steepness and orientation were made for more than 180 buried tunnel valleys in the central North Sea study area of this work.

- For the northern study area identified in Chapter 4, morphological measurements were made for each of the seven generations of tunnel valleys described in Chapter 5.
- In the southern study area (dataset M), morphological measurements were made for the three generations of tunnel valleys identified in Chapter 5.
- The remainder of the morphological measurements were based on the tunnel valleys in the regional dataset cnsmerge.

Quantitative geomorphological relationships are summarised below.

- Width measurements for all tunnel valleys varied between 300 m and 7000 m. Lengths of up to 117 km were observed, truncated only by dataset boundaries. Sinuositites were found to range between 1 and 1.14. Width to depth ratios for the majority of tunnel valleys range from 10:1 to 20:1.
- Most tunnel valleys displayed significant variations in their basal depth along their length. The basal relief is used as evidence that the tunnel valleys were formed subglacially by meltwater under pressure.
- The tunnel valleys show valley wall steepness measurements between 5 and 50°. Asymmetry is relatively common, but cannot be related to generation, aspect, or any assumed palaeoflow direction.
- About a quarter of the tunnel valleys in the study area display anabranching or significant meandering over tens of kilometres. Hanging valley relationships between tunnel valleys are observed at less than ten locations.
• The above descriptions are consistent with morphological measurements made for the feature tv1a, which is identified as the oldest generation in Chapter 5. Thus, tv1a can be considered a tunnel valley.

• In the northern study area, two of the cross-cutting generations of tunnel valleys identified in Chapter 5 can be separated on the basis of width, and, to some degree, planform complexity. Generation 2 tunnel valleys are relatively deep and narrow, with w:d values of less than 10:1. They show little evidence for complexity in planform, and are regularly spaced over the northern study area. Generation 4 tunnel valleys are notably wide and shallow (width to depth > 45:1) and are seen to re-occupy the former path of Generation 3.5 tunnel valleys.

• Orientation measurements for the tunnel valleys reveal a general NE-SW trend in the northern part of the study area (north of 57°30’N) compared to a NNW-SSE dominant trend in the southern study area.

• In the northern study area, orientation measurements show significant differences between generations. Generations 2 and 4 show a mean orientation of 065 while Generations 1, 3, 3.5 and 5 show a mean resultant direction of 035. Generations 6 and 7 do not display a preferred orientation.

• In Dataset M, Generation 1M displays a preferred orientation of 067. The mean preferred orientation for Generations 2M and 3M is 113.

Some conclusions can be made regarding tunnel valleys morphology, formation method and ice cover. The variety of forms observed in this work suggests that no single process is responsible for tunnel valley formation.

• Wide, shallow, tunnel valleys such as those observed in Generation 4 are considered to be a result of lateral erosion as a dominant erosive process during formation, and/or post-formation modification. Generation 2 tunnel valleys are suggested to be a result of more concentrated vertical erosion during formation, followed by rapid fill.

• Based on the wide range of observed orientations the majority of the tunnel valleys in the northern part of the central North Sea are not considered to have been proximal to an ice margin that remained fixed for a significant length of time, and are therefore implied to have formed towards the centre of extensive basin-wide ice sheets.
• The tunnel valleys in the southern part of the study area show a more pronounced orientation trend and are sub-parallel, indicating the influence of a proximal ice margin towards the south-east.
Figure 6.1 (a) Map showing the outline of all tunnel valleys (in black) imaged within Datasets A to J (in blue) in the northern part of the study area (north of 57°30'N) and from Dataset M (in blue) in the southern part of the study area (south of 57°30'N). Outwith these datasets, tunnel valleys were imaged within the dataset cnsmerge (outline in black), which links the two areas. (b) Summary of 3D seismic reflection dataset names and properties used in this work.
Figure 6.2 (a) Histogram showing frequency of tunnel valley width measurements in the northern study area from 410 measurements (b) Box plot showing the results of width measurements for tunnel valleys as separated into Generations 2 (G2) to 7 (G7). For each box, the median value is the central line, the lower and upper bounds of the box are the 25th and 75th percentiles of the data, and the t-bars indicate variance (see text for more detail). Dots show outliers. Number of measurements for each generation (n) included below key.
Figure 6.3(a) Basal profile a-a' from west to east along the Generation 7 tunnel valley tvn in Dataset A showing abrupt termination close to seabed. (b) Map of tunnel valleys in the western half of Dataset A showing the location of profiles a-a' and b-b'. Colours are the same used in Chapter 5 (c) Seismic profile showing the cross-cutting relationship between tunnel valleys tv0 (Generation 7) and tvf (Generation 3).
Figure 6.4(a) Histogram showing the frequency of sinuosity measures made for the tunnel valleys in the northern study area. Values of less than 1.1 are described as straight in the classification of Knighton (1998), those greater than 1.1 and less than 1.5 are described as sinuous.

Figure 6.4(b) Comparison of the distribution for the orientation measurements of the northern study area tunnel valleys (dotted line) to the von Mises distribution (thin line).
Figure 6.5 (a-g) Illustration of weighted orientation measurements as rose diagrams for the seven generations of tunnel valleys identified in the northern study area. Individual tunnel valleys referred to in the text are labelled. N equals number of measurements, f is the frequency of the outer circle of the rose diagram. The long profile (length versus depth) for the section of the tunnel valley tv5a from a to a' is shown in Figure 6.6.
Figure 6.6 (a) Line graph showing TWTT measured at the base of tv5a in Datasets A and B against distance along thalweg (from north to south). Vertical error bars are ± 12 ms TWTT (b) Long profile for tv5a showing the measurements in (a) converted to metres beneath seabed with error bars ± 6% (c) Internal depth of tv5a along its thalweg shown as metres above the deepest point (0) for comparative purposes. Error bars are ± 6%.
Chapter 6: Morphology of Buried Tunnel Valleys

Figure 6.7 Comparison of internal depths for northern study area tunnel valleys along reach shown as metres above their deepest point. Error bars are ± 11m.
Figure 6.8 Longitudinal seismic profile along part of the reach of tv3a in Dataset A illustrating the variation of relief in basal depth along thalweg (base in solid red). Tunnel valleys tv5a and tv5b cross-cut tv1a and their cross-sections are visible in this image (bases dashed in red). Location of profile is a-a' in Figure 6.5b.
Figure 6.9 (a) 3D surface showing anastomosing reach of tunnel valley tv3b (b) Terracing in tv5a (c) Anabranching channel in tv2a displaying a shallow spillway morphology (d) Location of examples a-c in the central part of the northern study area (see Figure 5.35).
Figure 6.10 (a) Seismic profile along line a-b in Dataset A showing a hanging valley relationship for a tributary of tvh (see Figure 5.5 for location) as well as the cross-cutting relationship with tve. (b) 3D surface for tvh in Dataset A showing the location of the seismic profile a-b and the morphology of tvh in general including valley wall steepness ($\Theta_1$ and $\Theta_2$). (c) Schematic diagram of a hanging valley.
Figure 6.10 (a-f) Examples of valley wall steepness (θ) in cross-section measured for tunnel valleys (a) tv2a (b)tv2b (c) tv6a (d) tvg in Dataset F (e) tv5a. (f) Locations of seismic profiles show in figures a to d. All profiles were measured from west to east, or north to south in the case of profile b.
Figure 6.12 (a) Tunnel valley tv1a as imaged in timeslice in Dataset H at 348 ms TWTT (approximately 148 m below seabed). (b) Tunnel valleys tv1a (solid red) and tv5a (dashed red) as imaged in timeslice in Dataset at 372ms TWTT (approximately 150 m below seabed). (c) Seismic profile along the line a-a” in Dataset H showing the base (solid white line) of the main channel of tv1a (a-a’) and three tributary channels (a’-a”). (d) Seismic profile along the line c-c’ in Dataset I showing the base of tv1a (solid red) and tv5a (dashed red). (d) Longitudinal profile (b-b’) for tv1a showing depth below seabed along thalweg. Error bars represent ± 12 m.
Figure 6.13a 3D surface for tunnel valley tv1a in Dataset H illustrating similarities in morphology to tv3b shown in Figure 6.13b. Both features exhibit anastomosing reaches and uneven thalwegs. Valley widths are also similar, although tv1a is generally shallower from base to shoulder.
Figure 6.14 (a) Three generations of tunnel valleys as interpreted from Dataset M. (b) Tunnel valleys as seen in Dataset M at 168 ms TWTT (approximately 56 m below sea level) where anastomosing geometries are clearly imaged. (c) Profile showing Generation 3 tunnel valleys (base in orange) in seismic cross section along the line a-a'. Note the strong seabed and base tunnel valley multiples. $\theta$ equals dip of valley walls. (d) Longitudinal profile of tunnel valley tvk along line b-b' showing concave-up profile even with the associated $\pm$ 20 m error.
Figure 6.15 Weighted orientation measurements for the three generations of tunnel valleys present in Dataset M.
Figure 6.16 Outline of all tunnel valleys mapped in the study area with associated orientation measurements for (a) all of the tunnel valleys in the northern part of the study area (north of 57°30'N) Outer ring of rose diagram equals a frequency of 90 (b) for Generations 1 - 7 in the northern study area (c) for Generations 1M, 2M and 3M in Dataset M (shaded in grey) and (d) for all of the tunnel valleys in the southern study area (outer circle of rose diagram equals a frequency of 20). Mean orientations (MO) are also included. Figure 6.16 shows the orientation measurements for the northern study area in more detail.
Figure 6.17 All tunnel valleys mapped from the northern part of the study area in Datasets A-I (outlined in red) and in cnsmerge (outline in black). Orientation measurements are shown as rose diagrams (outer circle equals a frequency of ten) for each generation of tunnel valley separated in the northern study area.
Figure 6.17a Two simplified models for wide tunnel valley morphologies. (i) Initial tunnel valley incised by meandering channel (ii) valley fills during ice retreat and is (iii) modified during readvance. Or, partially filled tunnel valley (iv) is modified in its upper parts by direct ice contact during readvance (v).

Figure 6.18b Possible sequence of re-occupation. (i) Generation 3 tunnel valleys completely filled prior to (ii) onset of glaciation and incision of Generation 3.5 tunnel valleys (in pink). Ice sheet retreats (iii), leaving Generation 3.5 tunnel valleys partially filled and present in landscape before readvance (iv) and re-occupation of Generation 3.5 by Generation 4 (green) tunnel valleys.
Chapter 7: Fill and Stratigraphy

Having considered the cross-cutting relationships and morphology of the buried tunnel valleys in Chapters 5 and 6, Chapter 7 of this work focuses on the fill of the buried tunnel valleys and their position in the stratigraphic framework of the central North Sea.

7.1 Tunnel Valley Fill

7.1.1 Background

The buried tunnel valleys and their infill describe Unit II of the seismic stratigraphy as defined by Graham (2007) (see Chapter 3.2.2.; Figures 3.5, 3.6) and characteristically display a highly variable acoustic character. Reconnaissance mapping of the tunnel valleys in this study drew on previous works investigating tunnel valley fill in the North Sea (Cameron et al., 1987; Praeg, 1996, 2003; Huuse and Lykke-Andersen, 2000; Kluiving 2003, Lonergan et al., 2006; Kristensen et al., 2007) which generally recognise a bi- or tripartite fill as shown in Figure 2.11a. In terms of seismic facies, these previous works in the North Sea often describe a chaotic and unstructured unit at the base of tunnel valleys, characterised by discontinuous reflectors of variable amplitudes, and overlain by layered, structured or transparent units (see Chapter 2.4 for additional background). Sub-parallel, continuous, moderate amplitude reflectors filling the upper parts of the tunnel valleys are also frequently observed.

Comparison of the seismic facies described above to limited borehole data available for the North Sea generally associate the structureless or chaotic layers with coarse, sandy glacio-fluvial sediments, and the well-layered units with muddy glaciolacustrine or marine sediments (Cameron et al., 1987; Long et al., 1988; Huuse and Lykke-Andersen, 2000; Praeg, 2003), although borehole data often displays sub-metre scale lithological variation. For example, the targeted seismic-lithostratigraphic correlations of Kluiving et al., (2003) finds sequences of coarse sands and gravels at the base of buried tunnel valleys in the southern North Sea produce the high amplitude discontinuous reflectors observed at the base of tunnel valleys. Thick middle units of variable seismic facies overlie the basal units and correspond to intercalated sands with complex fining and coarsening-up patterns which reflect variations in water-based depositional environments. Well-layered seismic facies in the upper part of the tunnel valley fill
correspond to coarse sands with an increasing percentage of clay, indicating deepening shallow marine conditions. The results of borehole analysis by the authors (see Kluiving et al., 2003, Figure 10, p.261) show cm-scale lithological variation indicative of complex, cyclical depositional environments.

As also discussed in Chapter 2.4, onshore works examining exposed tunnel find complex sequences of fill including tills, clays, sands and gravels, with variation at the metre-scale (see Ehlers and Linke, 1989; Piotrowski, 1994 for clear examples) More recent onshore work in Denmark by Jørgensen and Sandersen (2006) presents the results of exploratory boreholes drilled along thalweg of a buried tunnel valley which also show significant lithological variation at the metre-scale, precluding correlation along the valley and emphasising the complexity of the tunnel valley fill, as shown in Figure 7.1.

The examples above illustrate the complexity of fill present within buried and exposed tunnel valleys comparable to those studied here. In terms of the datasets utilised in this work, it was expected that much of the lithological variation in tunnel valley fill described above would not be resolvable in the 3D seismic reflection datasets, given their vertical resolution of between 7 and 10 metres. Changes in acoustic character below this scale would average out in the seismic reflection data, resulting in little or no indication of variability. Figure 7.2 highlights this issue of vertical resolution by comparing the infill of the same tunnel valley as imaged in the 3D seismic dataset cnsmerge used in this work with a high-resolution 2D seismic profile. Vertical resolution for the latter is as high as 1m, and its internal structures are clearly imaged in contrast to the profile obtained from cnsmerge. The three tunnel valleys present in Figure 7.2 show chaotic mixed amplitudes in the lower part of their fill, overlain by sub-parallel closely spaced low amplitude drape units (with some small bright amplitude patches).

Furthermore, although the works outlined above describe significant variations in lithology within the tunnel valley fill, much of the variation appears to be relatively gradual, for example, the cm-scale coarsening and fining in the sandy units within the borehole data acquired by Kluiving et al., (2003) and Jørgensen and Sandersen (2006). As seismic reflection techniques rely on significant contrasts in acoustic impedance to
generate reflections, it is no surprise that the data used in this work may not identify the more subtle changes in the sediments which fill the buried tunnel valleys.

Preliminary investigation of the infill of the buried tunnel valleys within this study revealed a diverse range of seismic facies with little evidence for regular patterning. Although some individual tunnel valleys displayed the structured fill described above and similar to that described by Kluiving et al., (2003) and Lonergan et al. (2006), many other valleys exhibited large packages of predominantly transparent or unstructured fill which formed irregular units up to 120 m in thickness and tens of kilometres in length. However, given the caveats on resolution and contrasting lithologies discussed above, this was not considered unusual and progress was made in resolving the nature of some of the larger scale sedimentological structures present within the tunnel valley fill. Outwith datasets A-M, in the merged dataset cnsmerge, vertical resolution was not sufficient to image the fill of the buried tunnel valleys, and phase and time shifts from the merged data adversely affected attempts at correlation across datasets as seen in Figure 7.2 (see also Chapter 4; example of imaging in seismic cross-section in Figure 4.1c).

7.1.2 Fill Observations

The base of the buried tunnel valleys were widely recognisable within the 3D seismic datasets as continuous high amplitude reflectors, as would be expected due to the significant difference known to exist between the lithology of the Aberdeen Ground Formation (comprising mainly marine clays) into which they incise, and the complex sand/gravel/clay/till internal fill of the tunnel valleys themselves. Some of the buried tunnel valleys displayed clear examples of the seismic facies (i.e. chaotic, transparent and drape units) described by other workers as discussed in Chapter 7.1.1 above, and these are outlined briefly below.

High amplitude, chaotic basal reflections described recently by authors such as Praeg (1996, 2003), Huuse and Lykke-Andersen (2000), Jørgensen and Sandersen (2003, 2006), Kluiving et al., (2003) and Lonergan et al., (2006) were identified within a number of tunnel valleys. The chaotic units, when present, were generally less than 30m thick, and displayed very poor continuity along thalweg. Figure 7.3a shows a typical example in cross-section within tunnel valley tvb in Dataset C where discontinuous,
high amplitude reflectors are conspicuous at the valley base. **Figure 7.3b** shows an example from tvb in Dataset F where the lower part of the tunnel valley is characterised by a thick (c. 50 m) package of disturbed medium to high amplitude reflectors. **Figure 7.4** shows continuous high amplitude reflectors present along the thalweg of tunnel valley tv3a in Dataset A and a package of chaotic reflectors c. 40 m thick extending for 2 km along the deepest part of its reach.

Units containing gently dipping reflections were sometimes observed within tunnel valley fills, as also described by Huuse and Lykke-Andersen (2000), Kluiving et al., (2003) and Lonergan et al., (2006). **Figure 7.5a** shows a cross-section of tunnel valley tvg in Dataset F (see **Figure 5.20** for location), where infill is entirely dominated by a largely seismically opaque unit with some discontinuous amplitudes in its upper part and low amplitude layering throughout. **Figure 7.5b** shows tunnel valley tvh in the same dataset, where a chaotic basal unit is overlain by weak, low amplitude flat-lying layering in the upper part of the fill. **Figure 7.5c** shows well-defined, continuously dipping reflectors within the fill of tunnel valley tvb in Dataset B. The arrowed bright spot appears to be a channel feature in the upper part of the dipping unit. **Figure 7.6** provides an example of one of the rare occasions where a middle unit of dipping reflectors could be traced laterally along the thalweg of a tunnel valley. **Figure 7.6a** shows a gently dipping reflection extending c.2.5 km along the reach of tunnel valley tvk in Dataset M. **Figure 7.6b** shows the feature as imaged in cross section. **Figure 7.6a** also displays a good example of a chaotic fill within tunnel valley tvb, which is cross-cut by tvk. Of note is the presence of a strong seabed multiple in the data.

Continuous, medium to high amplitude reflections appear to drape some of the top parts of the tunnel valleys in the study area, displaying similar seismic characteristics to the drape/onlap packages described by Huuse and Lykke-Andersen (2000), Kluiving et al., (2003) and Lonergan et al., (2006). **Figure 7.7a** shows an example from Dataset G where tvd, filled by a low amplitude unit with some disrupted irregular higher amplitude reflections is subsequently re-occupied by tvf, which contains well-layered fill with high amplitude, continuous reflections. Note the arrowed disruption within the well-layered package which could be a remnant of a partially preserved channel fill not visible in timeslice. The upper part of tvb in Dataset F also shows a good example of
high-amplitude continuous reflectors which appear to onlap the western flank of the valley as shown in Figure 7.3b.

A lack of shallow stratigraphic borehole control for the broad seismic facies identified in this study preclude detailed work on tunnel valley lithology, but qualitative analysis of the units correspond well to previous work in the area, allowing some conclusions to be made regarding the inference of lithological units and depositional environments. In general, this seismic facies identified in study agree with the works of Cameron et al., (1987), Praeg (1996, 2003), Huuse and Lykke-Andersen (2000), Jørgensen and Sanderson (2003, 2006), Kluiving et al., (2003) and Lonergan et al., (2006) which suggest the majority of the tunnel valley fill is composed of sandy material containing layers of coarse gravel and till, and is overlain by muds. The chaotic, high amplitude reflectors identified at the base of the tunnel valleys in this study are therefore consistent with their interpretation as coarse sand or gravel lags deposited during formation of the tunnel valleys by subglacial meltwater, or as tills deposited by direct ice contact. The asymmetrical geometry observed in the unit is also suggestive of at least partial deposition by mass movement following slope destabilisation subsequent to valley formation, as also suggested by authors in North Africa such as Hirst et al. (2003). All of the above depositional scenarios would result in the observed seismic signature and can be supported by the borehole studies carried out by the authors listed above. The example of a chaotic basal unit shown in Figure 7.4 which displays a length of c.2.5 km and depths of up to 40 m is unusual due to its relatively large scale; in general, the constraints imposed by the vertical resolution of the datasets used in this work did not allow for systematic mapping of the chaotic packages when present. Comparison with the high-resolution data shown in Figure 7.2 reveals chaotic metre-scale basal packages with uneven topography present within two of the tunnel valleys in the profile, and it is considered here that this unit is widespread but relatively thin in comparison with other tunnel valley fill units. Gently sloping units identified within some tunnel valleys (i.e. Figure 7.5c, Figure 7.6) are comparable to the wedge-shaped packages identified by Lonergan et al., (2006) and interpreted as subglacial meltwater deposits, although their occurrence was not widespread, and their geometry was not always resolvable. Transparent facies with gently sloping discontinuous reflections such as those showing in Figure 7.5a and 7.5b are also interpreted as predominantly sandy glaciofluvial deposits as in Ehlers and Linke (1988), Praeg (1996, 2003), Huuse and Lykke-Andersen
(2000), Kluiving et al., (2003), and Jørgensen and Sandersen (2003, 2006). The same authors generally associate well-layered units found at the top of the tunnel valley fill with clays and silts deposited during a return to glacimarine or glacilacustrine conditions.

The results of these observations indicate that the buried tunnel valleys in this study were filled in a variety of depositional environments, from high energy glaciofluvial flows to quiet glaci-lacustrine conditions. The lack of a systematic fill pattern for the buried tunnel valleys is most likely a result of the inability of the vertical resolution to image sub-metre scale changes in lithology, rather than a true reflection of tunnel valley fill conditions.

7.1.3 Tunnel valley fill and generations

As discussed in Chapter 5, the buried tunnel valleys in Dataset A-M were separated into cross-cutting generations, and the results of Chapter 6 show that a number of the tunnel valley generations display characteristic morphologies and orientations. Fill analysis of tunnel valleys was used to aid the separation of cross-cutting generations identified in Chapter 5 and to give an idea of the relative timing between episodes of tunnel valley incision. For example, Figure 7.8a shows the cross-cutting relationship between tunnel valleys tvd (Generation 2) and tvg (Generation 3) in seismic cross section and long profile in Dataset F. From the diagram, it can be seen that tvd (base dashed in white) displays a largely chaotic fill, with no evidence for structure in long profile. Tunnel valley tvg (base in black) clearly incises into the fully filled tvd where its u-shaped cross-profile is well-imaged, indicating a change in acoustic character between the fill of tunnel valley tvd and the unconformity which marks the base of tvg. Tunnel valley tvg also displays contrasting internal fill patterning, with a chaotic, discontinuous high amplitude basal package overlain by a package of dipping reflections. Such contrasts indicate that tunnel valley tvd was completely filled before the incision of tvg and so confirms the generational interpretation. Figure 7.8b provides a further example in terms of cross-cutting and apparent differences in fill but between tunnel valley tvk (base dashed white, Generation 5) and tunnel valley tvl (base is solid black, Generation 6) in Dataset I. This kind of relationship indicates the complete infill of tvk some time prior to the incision of tvl, implying a significant gap between the formation of the two tunnel valleys.
Figure 7.9 provides a further example of the fill relationship between three cross-cutting tunnel valleys from Generations 2, 6 and 7 in Dataset B. A seismic profile along the western channel of tunnel valley tvb, part of tv2b in Generation 2, reveals a significant sill along its base, but otherwise displays a seismically opaque fill. Tunnel valley tvn (Generation 6) cross-cuts tva almost at right angles and appears to display some gently dipping reflectors within its fill, and is then cross-cut by tvp (Generation 7) which appears to contain highly variable, discontinuous reflectors topped by a well-layered drape unit. Of note are the two distinct high amplitude flat lying events present within tvp which resemble stacked channels, although no evidence for expression is present in timeslice.

The cross-cutting relationship between Generations 3, 3.5, 4 and 5 was found to be less obvious, although interpretation of fill patterns for these generations assisted in their separation and the model of formation described in Chapter 6.3.3. Figure 7.10 illustrates an example from Dataset B where tunnel valley tvm forms part of tv4a, which defines Generation 4, tvh is part of tv5a, which defined Generation 5, and tvn is part of tv7a, which defines Generation 7. The seismic profile a-a’ illustrates the wide, shallow nature of tvm (base is white dashed), and where it deepens into tvh (base in black). The middle part of the infill for both tunnel valleys at junction x is indistinguishable (being largely opaque). A seismic profile along the line b-b’ shows the transition from tvm to tvh at location y, where fill is also homogenous. Tunnel valley tvn, however, clearly incises both channels and contains medium to high amplitude reflectors within its lower sections which distinguish it from the older generations. Table 7.1 summarises the qualitative findings of the examination of the seismic facies for the different tunnel valley generation in the northern part of the study area.

<table>
<thead>
<tr>
<th>Generations</th>
<th>Cross cutting supported by fill pattern?</th>
<th>Other factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 and 2</td>
<td>Yes</td>
<td>Stratigraphic difference</td>
</tr>
<tr>
<td>2 and 3</td>
<td>Yes</td>
<td>Many clear examples</td>
</tr>
<tr>
<td>3 and 3.5</td>
<td>Unresolvable</td>
<td>Only at one location</td>
</tr>
<tr>
<td>3.5 and 4</td>
<td>Inconsistent</td>
<td>Gen. 4 re-occupies Gen 3.5</td>
</tr>
<tr>
<td>4 and 5</td>
<td>No</td>
<td>Homogenous fill in parts</td>
</tr>
<tr>
<td>5 and 6</td>
<td>Yes</td>
<td>Clear differences in fill</td>
</tr>
<tr>
<td>6 and 7</td>
<td>Yes</td>
<td>Stratigraphic difference</td>
</tr>
</tbody>
</table>

Table 7.1 Qualitative summary of differences in fill patterns between Generations 1 to 7.
7.1.4 Morphological Features within tunnel valley fill

The 3D seismic datasets utilised in this work provided a unique opportunity to image the geometry of fill features within tunnel valleys. A number of what appear to be fluvial channels were imaged within tunnel valley infill, although apparently at the limit of lateral resolution (c. 25 - 50 m, dependant on bin size, see Chapter 4). Figure 7.11 shows a distinctly meandering channel present within the infill of tvb (which is part of the Generation 5 tunnel valley tv5a) in Dataset C. Figure 7.11a shows a seismic cross-section across profile a-a' where the channel is not apparent, but Figure 7.11b displays its clear presence in a timeslice at 380 ms TWTT. Channel width is approximately 100 m, an order of magnitude less than the width of tunnel valley tvb, and the feature displays significant meandering over a distance of less than 1 km. The scale and planform of the feature therefore suggest that it formed as a fluvial channel subsequent to the subglacial excavation of the tunnel valley in which it is contained, implying subaerial exposure during the period of tunnel valley infill.

Elongate features tens of metres in height and up to 3 km in length were imaged in at least three tunnel valleys in generations 3 and 5. Figure 7.12 provides the clearest example of such a feature in Dataset I. It displays a maximum height of c.60 m, with side-wall dips of between 3 and 4°, and is approximately 600 m wide at its widest point. The feature displays a relatively flat top and thins towards the north where it appears to have been dissected (see arrowed feature in Figure 7.12a). Investigation of the feature's internal seismic character (Figure 7.12c) reveals no apparent structure, although this is to be expected given the vertical scale of the feature (tens of metres) and the limit of vertical resolution for the dataset (7 – 12 m). A similar feature is also found at a smaller scale in the bottom part of tvg in Dataset F (Generation 3) and possibly within tvf in Dataset C (stage 3 in the 4-stage series for the dataset, see Figure 5.14).

The elongate features described above bear some resemblance to sections of flat-topped 'segmented' or 'beaded' eskers as described and categorised by Warren and Ashley (1994, see also Figure 11.30 in Benn and Evans, 1998, p.451), although they are larger than most features described as eskers (Benn and Evans, 1998). The base of the feature imaged in Figure 7.12 appears to sit conformably upon the undulating base of tvk, indicating subglacial formation by meltwater under pressure. As discussed in Chapter
2.3.3, authors such as Praeg (1996, 2003) view eskers as equivalent to tunnel valleys in terms of formation processes, with tunnel valley formation and esker deposition occurring contemporaneously depending on glacier bed conditions. Although there is little evidence within this study for extensive occupation of tunnel valleys by esker features (possible dependant on metre-scale resolution), it is considered that large scale (i.e. > 20 m in height and tens to hundreds of metres in width) esker-type features such as the one observed in Figure 7.12 were a result of deposition within discrete channels during tunnel valley excavation when large amounts of sediment were readily available. Their isolated nature may be explained by local variation at the glacier bed or by variation in discharge which encouraged deposition at these particular locations. Of note is the comparison between this esker feature and the elongate landform present in one of the seabed tunnel valleys described in Chapter 8.2.3.

The two conspicuous morphological features described above are both found within the tv5a tunnel valley, which stretches from north to south across the northern study area (see Figure 5.35 for location). The presence of resolvable morphological features in its reach suggest that the tunnel valley was infilled relatively slowly after its formation, in order for the channel and esker system described above to be formed and preserved, and therefore implies a significant gap between generation 5 and 6 tunnel valley. However, tunnel valley tv5a is also one of the larger tunnel valleys present in the dataset, and the imaging of morphological features within its reach may be a function of their size as resolvable in the 3D seismic datasets.

7.2 Regional Stratigraphy

7.2.1 Boreholes and Buried tunnel valleys

As discussed in Chapter 3, the fill of the buried tunnel valleys corresponds largely to Unit II within the regional seismic stratigraphy of Graham (2007). The only borehole in the region which penetrates buried tunnel valleys which are well-imaged in the 3D seismic datasets used in this study is BGS 77/02 in Dataset G (see location in Figure 3.1; Figure 5.23), work on which was originally published by Stoker et al., (1983, 1985) and more recently investigated by King et al. (1991) and Sejrup et al. (1994). Figure 7.13 illustrates the relationship between the formations identified within...
borehole 77/02, the regional stratigraphy of Graham (2007) and the generations of tunnel valleys identified within this work in Dataset G.

7.2.2 Tunnel valley tv1a

As described previously in Chapters 5 and 6, the Generation 1 tunnel valley, tv1a, is seen to incise from a lower level in the stratigraphy than Generations 2-7 (i.e. see Figure 5.27). Morphological measurements of tv1a reveal an undulating basal profile and enough significant similarities in form to the younger tunnel valleys (see Figures 6.12 and 6.13) to classify tv1a as a tunnel valley formed under pressure.

Correlation with the BGS borehole 77/02 within Dataset I indicates that the tunnel valley originates from just below the horizon associated with the Bruhnes-Matuyama (B-M) reversal at MIS 19 (0.78 Ma), as shown in Figure 7.14, placing it within Unit I of the seismic stratigraphy of Graham (2007) and confirming its age as older than that of the majority of the buried tunnel valleys, generally considered to be Elsterian (MIS 12) or younger in age (see Figure 3.5, Chapter 3.3). Regional mapping of the B-M time surface in the 3D seismic volumes confirms the incision of tv1a prior to the B-M reversal, as shown in three dimensions in Figure 7.15.

Graham’s 2007 work used regional correlation of the B-M event to identify two instances of iceberg scouring, indicative of glacial conditions, in the central North Sea prior to the Elsterian: one event at MIS 16 to the north, and at c. 1.8 Ma BP (MIS 31) in the south. Comparison with Graham’s (2007, p.360) interpretation indicates tunnel valley tv1a as being older than the iceberg scours identified in the northern study area (i.e. older than MIS 16), but younger than those to the south. Cold events indicated in the marine record at MIS 18 and MIS 22 (see Figure 3.2) could therefore be tentatively associated with the incision of tunnel valley tv1a, although further borehole control would be required to test this suggestion. In either case, a pre-Bruhnes-Matuyama age for tunnel valley tv1a is extremely significant in providing the first direct evidence for ice cover in the central North Sea during the Early to Mid Pleistocene.

7.2.3 Pre-glacial Features

During the process of mapping the margins of the buried tunnel valleys in the study area, a number of fluvial channels were imaged within Unit 1 of the regional seismic
stratigraphy which suggests that the northern part of the study area was subaerially exposed prior to the onset of the glacial conditions which initiated the formation of Generation 2 tunnel valleys. Figure 7.16 provides a clear example of a well-imaged fluvial channel flowing approximately NNE imaged in timeslice at 368ms TWTT and its limited expression in seismic cross-section. Tentative correlation with BGS borehole 77//02 suggests the channel is older than the Bruhnes-Matuyama magnetic reversal at c. 780 ka BP. Of note is the contrast in morphology between the fluvial channel imaged in Figure 7.16 and the tunnel valley tv1a, which appears to be of a similar age (Figure 6.12, 6.13, 7.15). Although tv1a displays a smaller cross-sectional profile in comparison to other buried tunnel valleys, it is clearly larger than the fluvial channel, and displays a much greater vertical expression.

Salt domes were imaged beneath 500 ms TWTT within Dataset M and cnsmerge towards the southern part of the study area. In contrast to the work of Praeg (1996) and Huuse and Lykke-Andersen (2000), who found that tunnel valleys were locally deflected by near-surface salt domes in the southern North Sea, the observed salt features did not appear to affect the morphology or fill of the tunnel valley present directly above them, as show for Dataset M in Figure 7.17. This is in line with other works in the central North Sea (Cameron et al., 1987) which consider salt tectonics to be of little relevance to the shallow Quaternary succession north of approximately 55°N.

7.3 Conclusions

Although an initial aim of this project was to map the individual seismostratigraphic formations that make up Unit II of the regional framework constructed by Graham (2007), a lack of borehole correlation, limitations in vertical resolution, and discrepancies in data quality between overlapping datasets meant that investigation of the tunnel valley infill was instead focused on qualitative comparisons to other, similar works, the clarification of the tunnel valley generations identified in Chapter 5, and the identification of morphological features within and outwith fill. However, a major result of this work is the discovery and confirmation of tv1a as a pre Bruhnes-Matuyama tunnel valley.

A number of conclusions regarding tunnel valley fill and their place in the North Sea stratigraphy can therefore be made in conjunction with the results of Chapters 5 and 6 of this work.
• The buried tunnel valleys within the study area display no consistent fill characteristics that can be imaged within the confines of the 3D seismic datasets used in this study.

• Some recognisable seismic units can be identified within the buried tunnel valleys, including packages of chaotic basal fill, seismically opaque units, and drape fills. Comparison with similar studies in the literature suggest these units indicate deposition in varying environments from high-energy fluvio-glacial meltwater channels to quiet shallow marine conditions.

• Differences in fill can be used to assist the separation of the tunnel valleys in the northern study area into cross-cutting generations, and the results support the groupings observed in Chapter 6 and discussed further in Chapter 9.

• A number of tunnel valleys contain morphological features including evidence for subaerial channels and elongate, esker-type features. These are used to indicate a significant gap between the incision and burial of the tunnel valleys in which they are imaged, but it is noted that their most distinct presence in one of the larger tunnel valleys may reflect that they are present but not well-imaged if found at a scale beneath the resolution of the available seismic data.

• Correlation with borehole 77/02 shows that tunnel valley tv1a is older than the B-M magnetic reversal at 0.78 Ma and provides the first direct evidence for ice cover in the central North Sea during the Early-Mid Pleistocene.

• Fluvial channels outwith the tunnel valley fill in Unit I of the regional seismostratigraphy suggest that the central part of the North Sea was exposed prior to the glaciations which formed the buried tunnel valleys.

• Salt structures present towards the south of the study area are not seen to affect the course of the tunnel valleys studied in this work.
Figure 7.1 Cross-section through four exploration drillings aligned along the thalweg of the Hornslyd Valley from Jørgensen and Sandersen (2006, Figure 9, p.1350). Lithological logs are shown with gamma ray measurements for each drilling and illustrate the structural complexity of the valley infill. The vertical resolution of the seismic datasets used in this work is c.8-10 metres, as shown, which is insufficient to resolve such detail.
Figure 7.2 Comparison of tunnel valleys imaged in (a) the regional dataset cnsmerge and (b) a high-resolution 2D seismic profile. Yellow line shown in (a) corresponds to the profile shown in (b). Detailed internal structure is apparent in (b) where two younger tunnel valleys (base in orange) incise into an older valley (base in red).
Figure 7.3(a) Cross section showing tunnel valley tvb (part of tv5a) in Dataset C (see Figure 5.13) where a chaotic basal unit of the tunnel valley fill is overlain by a middle unit of relatively transparent acoustic character. The base of tvb is shown as the dashed black line.

Figure 7.3(b) Cross section across tunnel valley tvb in the northern part of Dataset F (base in orange). Medium to high-amplitude discontinuous reflectors are present as the base of the tunnel valley.
Figure 7.4 Longitudinal seismic profile from south to north along tv3a (base in red) in Dataset A showing a continuous high-amplitude double reflection along its base, and the location of a c. 40 m thick high-amplitude chaotic unit towards its deeper section (shaded in blue). High amplitude reflections are also visible within the base of tv5a (orange) which cross cuts tv3a at this location.
Figure 7.5 Examples of faint or gently dipping reflections within tunnel valley fills in Dataset F. See text for details.
Figure 7.6 (a) Seismic profile along tunnel valley tvk in Dataset B showing a distinct package topped by a 2.5km long dipping reflection (arrowed) (b) The same feature imaged in cross section. (c) Location of the tunnel valleys and profiles in Dataset M. Note the strong seabed multiple.
Figure 7.7 Tunnel valleys in Dataset G showing an example of a well-layered, high amplitude seismic unit filling tunnel valley tvf (base in green), which is seen to re-occupy tunnel valley tvd (base in pink).
Figure 7.8 (a) Seismic profiles showing the relationships between tunnel valleys tvd and tvg in Dataset F (Generations 2 and 3) (b) Seismic profiles showing the relationship between tunnel valleys tvl and tvk (Generation 5 and 6) in Dataset I. See text for details.
Figure 7.9 (a) Seismic profile a-a' from Dataset B along tunnel valley tvb (b) Interpretations of seismic section (at same scale) showing the Generation 7 tunnel valley (tvp) cross-cutting a filled Generation 6 tunnel valley (tnv) which incises into a Generation 2 tunnel valley (tvb). Tunnel valley tvb shows little evidence for internal structure while tvn displays some gently dipping reflectors. Tunnel valley tvp contains discontinuous high-amplitude reflectors in its middle part (c) Outline of tunnel valleys in this example, see Figure 5.10 for location.
Figure 7.10 Tunnel valley relationships between Generations 3 to 6 in Dataset B. See text for description.
Figure 7.11 (a) Seismic cross-section showing tunnel valleys tvb and tva in Dataset C. (b) Timeslice at 380 ms TWTT showing a meandering channel (arrowed) within the fill of tvb not imaged in cross-section. (c) Location of profile a-a'.
Figure 7.12 Elongate esker-type feature present in tunnel valley tvk in Dataset I. (a) 3D surface created for the feature in GeoProbe software package. Blue surfaces are valley walls. Vertical exaggeration is x 16. Arrow shows dissection of the feature. (b) The feature imaged in timeslice at 316 ms TWTT (c) Seismic cross profiles a-a' and b-b' showing the feature as imaged within tvk and its narrowing to the north. (d) Location of tunnel valleys and profiles within Dataset I.
Figure 7.13 Core-seismic tie for BGS borehole 77/02 and seismic data in Dataset G showing BGS formations and the seismic stratigraphy constructed by Graham (2007). See text for details of BGS Formations.
Figure 7.14 Seismic profile showing tunnel valley tv1a (base in white) imaged in Dataset I and the BGS borehole 77/02 with BGS stratigraphic correlation located c. 2 km to the south east of the section shown. Tunnel valley tv1a is seen to incise from just below the reflector correlated to the Bruhnes-Matuyama magnetic reversal in the borehole, above the Pliocene-Pleistocene boundary.
Figure 7.15. Three dimensional views from two angles of the 3D seismic volume from Dataset H displaying tunnel valleys tv1a and tve (see Figure 5.26 for location) and their relationship to the Brunhes-Matuyama (B-M) magnetic reversal shown here as an interpreted time surface. Vertical scale is TWTT (ms). Tunnel valley tv1a can clearly be seen to incise from beneath the base of the B-M horizon (at 322 ms TWTT) while tunnel valley tve originates from a higher stratigraphic level at 160 ms TWTT.
Figure 7.16 (a) Timeslice at 368 ms TWTT showing tunnel valley tve in Dataset A and a fluvial channel (outlined in yellow) outwith the valley fill. (b) Seismic cross-section a-a' in Dataset A showing the well-imaged tunnel valley tve and the vertical expression of fluvial channel circled in red. Tie to the B-M event from BGS borehole 77/02 is shown dashed in red. (c) Location of profile a-a' in Dataset A.
Figure 7.17 (a) Seismic profile a-a’ in Dataset M showing the effects of a salt dome at depths greater than 400 m beneath seabed and the base of the buried tunnel valleys at approximately 150 ms TWTT. (b) Timeslice at 696 ms TWTT showing the circular form of the salt dome. (c) Timeslice in same location as (b) at 264 ms TWTT showing two cross-cutting tunnel valleys not affected by the presence of the salt structure directly beneath. (d) Location of profiles and timeslices in Dataset M.
Chapter 8: Seabed Tunnel Valleys

Although the existence of significant seabed depressions offshore north-east Britain has been recorded in the literature since at least the nineteenth century (De La Beche, 1834), and form part of the work by the British Geological Survey on the stratigraphy of the North Sea (see Chapter 3; Stoker et al., 1985; Stoker and Bent, 1985; Long and Stoker, 1986; Cameron et al., 1987; Wingfield, 1990; Jeffrey, 1991; Balson and Jeffrey, 1991; Johnson et al., 1993; Gatilff et al., 1994), it is only recently that geophysical work has focused on the bathymetry of the North Sea in enough detail to fully complement shallow seismic surveys and 3D seismic reflection datasets. The thin, linear nature of the incised features, whether at seabed or buried, pose the same methodological problem for survey spacing in either case – they can be easily overlooked depending on grid spacing (see Chapter 4.1 for more details). The merged bathymetric database, Olex, processed and managed by the Norwegian company Olex AS (www.olex.no) comprises echosounder data obtained by commercial fishing boats and research vessels with excellent coverage over the central North Sea study area of this work.

The Olex dataset allows for unprecedented analysis of seabed geomorphology in the central North Sea, with a number of significant glacial landforms present, including channel features variously interpreted as seabed tunnel valleys or meltwater channels. Data is presented in 5 x 5m bins, located by GPS with positional error less than 10m. Vertical resolution is 1m in water depths greater than 100m and 0.1m at depths less than 100m. Relative depth errors are less than 2% with the speed of sound in water harmonised to 1500ms⁻¹ (Bradwell et al., 2008, p. 7).

With the assistance of Christian Wilson and Tom Bradwell at BGS it was possible to access a seabed model of the Olex database as used by Bradwell et al (2008) and further analysis of the tunnel valleys was conducted. Based on a number of recent borehole ¹⁴C dates for subglacial tills found beneath the seabed tunnel valleys (Graham et al., 2007) the seabed tunnel valleys are interpreted as Late Weichselian (MIS 4 – 2) or Last Glacial Maximum (LGM) in age (see Chapter 3 for more details). LGM is defined as in recent work by Bradwell et al. (2008) as equivalent to Marine Isotope Stage 2 and
spanning 30-22ka BP with maximum extent around 26ka BP. Freshness of morphology, with sharp valley wall edges and preserved uneven basal profiles, also provides morphological evidence that the channels were formed during the most recent glacial episode.

Bradwell et al. (2008) have mapped the offshore channels as observed in the Olex dataset as part of a seabed landform assemblage used to support a new three-stage model of LGM ice-sheet maximum and retreat. The authors map and divide the channels into two groups: Group A, which are described as trending north to northwest, and are distributed across the northern North Sea, and Group B: nearshore channels lying close to the coast of eastern Scotland (Bradwell et al. 2008, p.7, Figure 5, p.9). Both groups present undulating basal profiles and are interpreted as subglacial meltwater channels, with Group A identified specifically as tunnel valleys. The Group A tunnel valleys are associated with large arcuate moraines present at the shelf edge northwest of the Shetland and Orkney islands, trending roughly perpendicular to the tunnel valleys (Bradwell et al., 2008). Together, these are used to provide evidence for an extensive continental ice sheet draining broadly to the northwest, corresponding to the first part of the three stage model representing maximum LGM glaciation as a result of confluent, grounded, British and Fennoscandian ice sheets. Group B channels are associated with the proposed third and final stage of deglaciation, characterised by nearshore ice streaming and the effect of local relief on an independent British Ice Sheet.

This study is in general agreement with the three-stage LGM model proposed by Bradwell et al. (2008), particularly with respect the timing of LGM and the idea of a dynamic, confluent and grounded ice sheet at maximum extent. Comparing seabed and buried tunnel valleys in this context allows progress to be made in reconstructing North Sea ice sheet configuration at different times during the glacial cycles of the Pleistocene, as well as offering insight into formation mechanisms for tunnel valleys.
8.1 Location and Morphology of Seabed Channels

From the Olex dataset, four groups of channels with seabed expression in the central North Sea are separated with respect to location: two near-shore meltwater channel/tunnel valley systems (here identified as the Moray Firth and Montrose Groups), and two offshore sets of tunnel valleys – the Fladden and Devil's Hole groups. The latter two groups in particular are similar enough in character to the buried tunnel valleys examined in the rest of this work to be of significant interest.

The Fladden Group comprise 21 well-constrained seabed tunnel valleys situated to the north and west of the Witch Ground Basin, fairly evenly spaced between 2°W and 2°E and extending approximately 200km north of 58°N (see Fladden Group, Figure 8.1). The Devil's Hole group contain 13 interpreted tunnel valleys in an area stretching 150km north of 56°N and again approximately evenly spaced between 1°W and 1°E (see Devil's Hole Group, Figure 8.1). The Moray Firth group are situated in the eastern outer Moray Firth in a 110 x 60km area, near-shore to the Moray coast, while the Montrose Group follow the coast of Scotland north-east from Montrose, covering an area of approximately 100 x 100km.

The channel features were digitised and their geometry measured in ArcGIS 9.0 (ESRI). Measurements were rounded to the nearest metre in depth measurement, and 10m in width and length to account for interpreter error.

For all the seabed channels, average widths and depths were less than 1.5 km and 67 m respectively. Channels are relatively shallow and wide, with typical width to depth ratios being greater than 20. All of the channels in the groups start and terminate abruptly, a very common feature of landforms described as subglacial tunnel valleys in other North Sea studies (O'Cofaigh, 1996; Huuse and Lykke-Andersen, 2000; Kristensen et al., 2006; Lonergan et al., 2006; Kristensen et al., 2007).

The Fladden Group channels display a preferred NNW/SSE orientation (mean resultant direction 164°-344°, see Chapter 4.2.1) with a slight NNE component (see Fig 8.2a). Measurements for channel plan-form shows sinuosities between 1.1 and 1.28, within
the lower end of the "sinuous" range of fluvial classification (see Chapter 2.3; Knighton, 1998). At least four channels display branching with join angles in the region of 20 - 30°. Towards the north west of the Fladden Group there are a number of very shallow indistinct linear depressions with similar channel plan-form which are considered near-filled remnants of the seabed channel systems in the group and noted as features C in Figure 8.2a. The majority of the Fladden Group incise entirely into Quaternary sediment at least 80m thick (generally 100 – 200m), with the exception of the channels on the eastern margin of the Moray Firth between 1° and 2°W, where Quaternary sediment thins out to less than 10m (Andrews et al., 1990; Gatliff et al., 1994).

Further to the south, the Devil’s Hole Group of channels trend strongly NNE/SSW (mean resultant direction is 002°-182°) with a slight NNW/SSE component (see Fig 8.2b). Channel plan-forms display slightly less variation in direction than the Fladden Group, with sinuosities ranging between 1.01 – 1.06, therefore “straight” in the fluvial classification (Knighton 1998). Two clear instances of branching are noticeable with join angles up to 40°. All channels cut into at least 200m of Quaternary sediment (Gatliff et al., 1994).

Measurements of internal depths (from shoulder to deepest part of channel) in the Fladden and Devil’s Hole Groups show a maximum of 195m (295m below sea level) in channel ‘tv11’ shown in Figure 8.2a, although typical internal depths are approximately 60 m and there is significant variation within channel, as discussed below (see Figure 8.4). The seabed channels are typically v to u-shaped in cross-section, with many displaying asymmetry in valley side steepness, although not with any preference to aspect or bend direction. Cross-sectional profiles are shown for both groups in Figure 8.2c and d and at the same scale for comparison with the nearshore groups in Figure 8.4.

The Moray Firth Group of seabed channels trend in a general E/W direction, with mean resultant direction at 095°-275° (parallel to the Moray coastline) and some reaches displaying a NW/SE minor component. The channels display an anastomosing to braided plan-form apparently converging to the east. Sinuosities average 1.1, although this is not necessarily representative of the ‘braided’ channels, which are inherently
more sinuous when analysed as a whole (see BC in Figure 8.3a). Quaternary sediments are generally less than 20m thick west of 2°W (Andrews et al., 1990) although thicknesses of up to 60m are observed in small basins in the southern Moray Firth, corresponding to the location of the western channels and Southern Trench (ST in Figure 8.3a, see Andrews et al., 1990, p. 63).

The Montrose Group channels show a preferred NE/SW orientation with mean resultant direction at 049°-229°, trending parallel to the current coastline. Many channels display significant branching (to the south-west) to produce an apparently anabranching plan-form with inter-channel ‘islands’, although some isolated channels are present outwith the system (see Fig 8.3b). Join angles range from 20° to 30°. Despite the anabranching plan-form, individual reaches of the majority of the channels are fairly straight, with average sinuosities less than 1.1. Quaternary thicknesses in the area are generally less than 40m (Gatliff et al. 1994 p.83).

Analysis of the Moray Firth Group of nearshore channels show slightly smaller cross-section dimensions compared to the offshore groups, with the exception of the Southern Trench (ST in Figure 8.3a; see Andrews et al., 1990; Bradwell et a., 2008). The braided channels to the north-east of the area (see BC Figure 8. 3a) are shallower (10 - 30m internal depth) and narrower (550m average shoulder to shoulder width) than those in the offshore groups, but comparable to the Montrose Group nearshore channels as seen in Figure 8.3b which exhibit a more subdued bathymetric form, average widths being less than 700m and internal depths less than 40m. Figure 8.4 provides scaled comparisons for selected profiles in each group.

Valley wall steepness for all groups ranges from 1° to 17° and generally averages between 4° and 5°, measured as described in Chapter 4.2. Kristensen et al. (2007) measured flank dips for 15 buried tunnel valleys in the Danish sector of the central North Sea, and recorded average values of 15 – 25°, with maximum angles of up to 45°, significantly steeper than the surface channels in the Olex dataset. 67% of the seabed channels display some asymmetry in valley wall steepness, recorded where there is a difference of 1° or more in flank angle at one cross section. 21% display a difference of greater than 5°. Measurements are comparable to those analysed by Kristensen et al. (2007) who report 68% with one percent and 27% with 5 percent difference in flank
dips. Although asymmetry is present, there is no evidence within the data to link flank aspect to steepness, as used by Long and Stoker (1986) to infer periglacial formation or modification of the channels. Flank steepness measurements also fail to provide any evidence for palaeo-flow direction (i.e. consistent steepening on the outside of bend in the direction of flow). Table 8.1 summarises the morphological measurements for the seabed tunnel valleys investigated in this work.

<table>
<thead>
<tr>
<th></th>
<th>Fladden</th>
<th>Devil's Hole</th>
<th>Moray Firth</th>
<th>Montrose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Width (km)</td>
<td>1.43</td>
<td>1.4</td>
<td>1.31</td>
<td>0.99</td>
</tr>
<tr>
<td>Maximum Width (km)</td>
<td>2.5</td>
<td>2.3</td>
<td>2.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Lengths</td>
<td>3 - 60km</td>
<td>3 - 40km</td>
<td>1 - 65km</td>
<td>2 - 50km</td>
</tr>
<tr>
<td>Average Sinuosity</td>
<td>1.15</td>
<td>1.04</td>
<td>1.11</td>
<td>1.02</td>
</tr>
<tr>
<td>Maximum internal depth (m)</td>
<td>150</td>
<td>102</td>
<td>125</td>
<td>51</td>
</tr>
<tr>
<td>Average internal depth</td>
<td>42</td>
<td>58</td>
<td>68</td>
<td>38</td>
</tr>
<tr>
<td>w:d</td>
<td>20 - 80</td>
<td>15 - 50</td>
<td>Nov-30</td>
<td>22 - 33</td>
</tr>
</tbody>
</table>

Table 8.1 Summary of morphological measurements for the four groups of tunnel valleys imaged at seabed.

The majority of channels in all of the groups display an irregular thalweg and not the downstream basal gradient increase typical of a fluvial system. Figure 8.5 shows significantly undulating longitudinal profiles for channels within the Fladden Group, with deeps greater than 40m beneath average basal depth extending up to 7 km, and highs of 70m above base level (see Chapter 6.1.1.5 for more on comparative long profiles). Figure 8.6 demonstrates this phenomenon further with an oblique view along an undulating channel looking NNW from point A in Figure 8.2a. As discussed in Chapter 2, and from the findings of Chapter 6 of this work, and by Huuse and Lykke-Andersen (2000), Lonergan et al. (2006), and Kristensen et al. (2007), the presence of a significantly undulating longitudinal profile with multiple thresholds is viewed as evidence for a subglacial origin for the channels, where pressurised meltwater is sufficient to provide uphill flow.

The quality of the Olex dataset meant that end slopes for a number of channels were able to be measured with some certainty, and found to range from 0.7 - 8° with average values around 3°. No apparent relationship was found to link end steepness to aspect and/or orientation. Similar measurements made by Kristensen et al. (2007) for buried tunnel valleys show steeper end slopes, averaging from 2.5° to 13°. Kristensen et al (2007, p.810) use their morphometric measurements further in order to test methods of
formation for their buried tunnel valleys, proposing that hydraulic head will be sufficient to drive water at the ice-bed interface uphill towards the ice margin if bed slope at margin is "less than eleven times the ice-surface slope". Using the formula \( h = A \cdot L^{1/2} \) (Paterson 1994), where \( h \) is ice thickness, \( L \) distance from margin, and \( A \) a coefficient dependent on ice temperature and properties of glacier (assumed as \( A = 1 \) for a warm based glacier on a soft bed, typical of reconstructions for the north-west European ice sheets), Kristensen et al. (2007, p.810) find that all of their end slopes allow for the uphill flow of meltwater from glacier bed to margin. The seabed channels in the Olex dataset all display shallower end slopes (<13°) at both channel ends, and are therefore also consistent with subglacial formation, uphill flow towards the ice margin being physically possible.

Branching angles and orientation do not shed light on flow direction for the Fladden and Devil's Hole Groups. 'Branching' is used here, as discussed in Chapter 2.3.2, as a descriptive term to indicate a tunnel valley with more than one channel. In general, branching refers to the confluence of two (or more) channels – a secondary tributary joining the main flow thoroughfare. This pattern is the one most familiar in fluvial geomorphology and implies a flow direction downstream from the join. Channels may also undergo divergence, where the main channel splits in the direction of flow, usually resulting in braided, anabranching, or anastomosing plan forms as discussed in Chapter 2.3 (Rosgen 1994; Knighton 1998; Charlton 2000).

The Fladden and Devil's Hole tunnel valleys in this study show no directional consistencies in branching patterns, and therefore can give no inference of flow direction. For example, in Figure 8.2a two clear examples of tunnel valleys with more than one channel are shown at locations B and C. At location C, the channel splits towards the south-east, whereas at location B the channel splits to opposite direction, north-west. However, it is not possible to ascertain whether either split is a result of divergence or convergence of the main channel. In the former case, the tunnel valley at location C would exhibit south westerly palaeoflow, and location B north-westerly flow. If the latter, C shows flow to the north-west and B to the south-east.

Branching in the Moray Firth and Montrose groups display more directional consistency, with secondary channels merging towards the east and northeast.
respectively (see Figure 8.3). Assuming that drainage is dominated by proximal onshore systems (during glacial or interglacial periods), as also suggested by Merritt et al. (2003) and Bradwell et al. (2008), branching as a result of divergence towards the coast (i.e. flow from the east towards land) can be dismissed, indicating instead palaeoflow downstream from confluence, eastwards in the case of the Moray Firth channels, and to the north east for the Montrose Group. Less clear are the apparently braided channels present to the east of the Moray Firth Group (BC in Figure 8.3a) although their planform can also be interpreted as a result of flow to the south east.

8.2 Interpretation of Olex Seabed Channels

8.2.1 Moray Firth and Montrose Groups

Most of the Moray Firth and Montrose channels display a distinctive irregular base, but differ from the Fladden and Devil’s Hole group tunnel valleys in that they show more developed patterns of directionality in planform. Cross-sectional geometry tends towards shallower, narrower channels, with the exception of the Southern Trench in the southern Moray Firth (ST in Figure 8.3, Bradwell et al., 2008; Merritt et al., 1995; Andrews et al., 1990), where magnitude and direction are directly influenced by a major Triassic-Cretaceous fault in the locality (Andrews et al., 1990). It is possible that the feature existed as a pre-Quaternary depression, re-used as a drainage channel at the onset of Pleistocene glaciations. The ‘braided’ channels (BC in Figure 8.3) to the east of the Moray Firth Group, and the anastomosing channels of the Montrose Group, bear a strong resemblance to ‘Nye’ type subglacial meltwater channels (Benn and Evans, 1998; Nye, 1973), and share dimensions with the Labyrinth bedrock meltwater channels found in Victoria Land, Antarctica (Sugden et al., 1991; Shaw and Healy, 1997; Lewis et al., 2006). The bedrock channels as studied by Lewis et al. (2006) and the seabed braided channels in the Moray Firth Group are compared in Figure 8.7.

It is possible, therefore, that the smaller dimensions and planform geometry of the Montrose and Moray Firth Groups of channels reflect their use more as ‘linked — cavity’ type (Benn and Evans, 1998) subglacial meltwater channels. The comprehensive Olex database reveals no further seabed channels off the east coast of Scotland, and Holocene sedimentation in the area is insignificant (< 11m; Fyffe, 1983) in comparison to the
dimensions of the observed channels. Therefore, this dataset confirms the spatial distribution of the nearshore channels to the Moray Firth and Montrose locations only. The formation of the channels must be related therefore to some process only operating in the Moray Firth and Montrose areas during the LGM. In agreement with recent work by Merritt et al. (1995, 2003), and Golledge and Stoker (2006), it is suggested that the location and form of the Montrose and Moray Firth Groups of channels are related to the location and behaviour of BIS ice streams active in these areas during the LGM.

Evidence for a fast flowing ice-stream in the Moray Forth area, dominant just before the final stages of deglaciation has been considered by authors such as Merritt et al. (1995, 2003) and Bradwell et al. (2008). Oscillating ice-sheet behaviour in the area, suggested by Bradwell et al. (2008) during the middle stages of deglaciation, would imply rapid changes in dominant erosive processes and could account for the variation in channel form. The braided channels shown in Figure 8.7 resemble proglacial drainage channels, and may have formed during subaerial exposure. It is noted that although the Southern Trench appears to follow the path of a major Mesozoic fault in the area, the other channels in the Moray Firth Group bear no relation to nearby fault-line trends (Andrews et al., 1990).

Similarly, the Montrose group of channels may result from enhanced subglacial meltwater drainage to the north-east relating to an ice stream around the Firth of Tay and Strathmore during the final stages of the LGM deglaciation, as suggested by Golledge and Stoker (2006). The authors claim a dominant north-easterly flow direction for the ice stream during the latter stages of deglaciation, a result of topographic constraints (to the north by the Grampian Highlands and to the south by the Sidlaw Hills in Fife) and the dominance of ice streaming from the Western Highlands accumulation zone. Offshore seabed channels trend strongly in the same direction near to onshore elongate features associated with the ice stream, and are seen to incise into the Wee Bankie moraine complex, now thought to mark the extent of an independent BIS Readvance post-LGM maximum ca. 18 – 24 ka BP (Carr et al., 2006; Golledge and Stoker, 2006; Bradwell et al., 2008). The above suggest formation of the channels during the final stages of LGM deglaciation, between approximately 18 ka BP and 16 ka BP when the Montrose coast was known to be ice-free (Cullingford and Smith, 1980; Armstrong et al., 1985).
Unfortunately, the relationship between the proposed ice streams and channels at both locations are not straightforward. Flow lines presented by Golledge and Stoker (2006, p. 238) for the Strathmore ice stream do follow the orientation of the Montrose Group channels, although it appears the authors have used the presence of the channels themselves as evidence to directly support a north easterly flow direction. However, there is some controversy in linking the subglacial processes present within an ice stream and tunnel valley formation; apart from that the former necessitates high volumes of meltwater requiring evacuation. Work in Antarctica (Lowe and Andersen, 2002; Evans et al., 2004; Smith, 2007) contradicts the idea of tunnel valleys as forming within ice streams, and tends to consider their locations as mutually exclusive. Work on the Minch ice stream in north-west Scotland and the Hebridean shelf (Bradwell et al., 2007) is noticeable for its absence of offshore meltwater channels or tunnel valleys. This work considers the effect of Quaternary sediment distribution and the dynamics of local ice streams as possible factors influencing the location of the Moray Firth and Montrose seabed channels.

A significant link between the two groups of nearshore channels is the presence of potentially deformable sediment in the areas where the channels are found today. Although the depths of Quaternary sediment present in the Moray Firth and Strathmore ice streaming regions (generally west of 1° W) are thin in comparison to the central North Sea and Witch Ground Basin, it is still of note that the channels are found incised into at least 20 - 40m of Quaternary sediment (see Chapter 3, Figure 3.3 and 3.4). The Moray Firth channels, in particular, correspond strikingly to the small Quaternary basins nearshore to the Moray coast, with no evidence for offshore channels near the Caithness coastline where the Moray Firth was deflected and drained NNW, and where Quaternary sediment is thin (< 10m) or absent (e.g. Andrews et al., 1990, Figure 56, p.63).

Also significant is the link between the location of the nearshore channels observed today and the position and behaviour of the Moray Firth and Strathmore ice streams. Bradwell et al. (2008) suggest that the Moray Firth and Montrose Groups of channels were features of the final stages of deglaciation of the British Ice Sheet (less than 18 ka BP) and represent drainage from smaller-scale ice streams than those present at LGM...
maximum, and controlled by topographic onshore constraints due to thinning of the ice-sheet to less than 450m (the maximum height of the Sidlaw Hills). The authors propose that at this point the BIS underwent mass loss due to significant melting and drawdown, rather than as a result of sea level rise and calving processes, which are thought to have dominated the break up of the larger BIS/FIS ice-sheet during LGM maximum. Under these conditions, the nearshore channels are associated with the margins of a relatively stable but geographically constrained ice streams in the Moray Firth and Strathmore areas.

Consequently, the smaller dimensions for the Montrose and Moray Firth Groups in comparison to the Fladden and Devil’s Hole Groups are a result of their relatively younger age, and their coherent direction in channel planform is related to dominant localised ice streams which influenced their location and form. More work is needed to quantify the properties of these ice streams and their relationship to the channels, particularly as their formation was undoubtedly at least originally subglacial, and because of a lack of other work linking contemporary ice streaming in Antarctica and Greenland to the formation of tunnel valleys. The incision of the Montrose Group channels into the Wee Bankie moraine complex suggests their incision after the period of relative stability, with formation during the final deglaciation of the LGM ice sheet (Bradwell et al., 2008; Golledge and Stoker, 2006).

Here, it is proposed that retreat of the ice margin, and the formation of subglacial channels, progressed headwards along the path of the former ice streams. The isolated nature of the Montrose and Moray Firth offshore channels may result from the relatively rapid retreat of offshore grounded ice and a subsequent lack of similarly sized erosive channel features onshore. Rapid retreat also provides reinforcement for the concept of ice-retreat along the course of the former ice streams – the internal configuration of the BIS would still encourage drainage focused on the path of the (topographically controlled) ice streams, thus encouraging draw-down and melting into these conduits, which would provide a sufficient concentration of pressurised meltwater to initially form the subglacial meltwater channels. This scenario avoids the problems associated with coeval ice streaming and tunnel valley formation, as the Strathmore and Moray Firth ice streams would be effectively ‘switched off’ during this final stage of
deglaciation, while rapid retreat along their former paths encouraged the incision of the nearshore channels.

In summary, it is inferred that the processes that formed the Montrose and Moray Firth Group channels were quite different for those seabed tunnel valleys in the central North Sea, and instead reflect the character of locally constrained BIS ice streams in the region, as well as the scarcity of Quaternary sediment nearshore. During the final stages of LGM deglaciation, the nearshore channels formed subglacially along the courses of former localised ice sheets as organised pathways for subglacial meltwater in the style of large Nye-type channels initially cut into relatively soft substrate.

8.2.2 Fladden and Devil's Hole Groups

The morphology, scale and location of the Fladden and Devil's Hole Group seabed channels examined using the Olex dataset are similar enough to that of other well-studied North Sea tunnel valleys to classify them as such with some certainty (Huuse and Lykke Andersen, 2000; Lonergan et al., 2006; Jørgensen and Sandersen, 2006; Kristensen et al., 2007). In particular, the presence of a significantly undulating base in the majority of the seabed channels, and their abrupt initiation and termination with relatively steep end slopes, confirms their origin as subglacial, a view recently supported by the morphological work of Lonergan et al. (2006) and Kristensen et al. (2007) and in Chapter 6 of this work.

Recent work by Sejrup et al. (2000, 2005); Carr et al. (2006), Graham et al. (2007) and Bradwell et al. (2008), confirm that the central and northern North Sea was overrun by an extensive ice sheet during the last glacial maximum ca.30 – 25 ka BP. Work by Graham et al. (2007) and Bradwell et al. (2008) implies that the Fladden and Devil's Hole tunnel valleys were formed beneath a coalesced British ice sheet (BIS) and Scandinavian ice sheet (SIS) during this period of maximum extent. Certainly the broadly north-west orientation of the Fladden Group tunnel valleys and the presence of large moraines and glacially fed fans on the shelf edge to the north west suggests dominant drainage in this direction, at least for the northern part of the central North Sea (Bradwell et al., 2008; Sejrup et al., 1994, 2000, 2005). A lack of similar
depositional features to the south provides further evidence for north-westerly palaeoflow (Gatliff et al., 1994). An ice stream flowing north-west during maximum extent of a coalesced BIS/FIS, as proposed by Graham et al. (2007), also provides evidence for a north-westerly palaeoflow. This configuration is shown in relation to the Fladden and Devil’s Hole Groups in Figure 8.8, where the shaded area represents confluence between the British and Fennoscandian ice sheets, and the black arrows mega scale glacial lineations indicating flow to the north-west (Graham et al., 2007; Bradwell et al., 2008). The Fladden and Devil’s Hole groups of tunnel valleys can be interpreted as trending roughly parallel to the flow lines of the coalesced ice sheet, following a north-south orientation south of 58°N and trending to the north-west north of 58°N. The simplest method for their formation would be as subglacial tunnel valleys formed beneath the ice sheet at maximum extent when the dominant drainage direction was to the shelf edge.

Although the model of northern North Sea ice configuration at LGM maximum extent, as suggested by Bradwell et al. (2008), implies contemporaneous tunnel valley formation and a ‘convergence zone’ associated with an ice stream extending towards the Fair Isle channel (and possibly to the shelf edge through the Fair Isle channel), it is not clear how the Devil’s Hole and Fladden tunnel valley formed with respect to the ice stream. Furthermore, there is a distinct lack of seabed tunnel valleys in the vicinity of the Witch Ground Basin where the MSGL package identified by Graham et al. (2007) is used to support the presence of a NW flowing ice stream. Rather, the Devil’s Hole and Fladden Groups of tunnel valleys are located in discrete bands to the north and south of the basin, as shown in Figure 8.8.

A number of possible scenarios relating tunnel valley formation, ice streaming, and a coalescent BIS/FIS can be envisaged in order to resolve the problem, although these proposals are constrained by the lack of a full understanding of the genesis of tunnel valleys beneath continental ice sheets as discussed in Chapter 2 and the paucity of chronological control for the central North Sea as outlined in Chapter 3.

One possibility is that a Witch Ground ice stream, while otherwise active during maximum extent of the LGM, terminated abruptly to the south of the Fladden Group, providing an ample supply of meltwater to form the tunnel valleys under stagnant ice. In
other words, the WG ice stream, driven by overflow from the Norwegian channel to the south-east, was then confined to the Witch Ground Basin area during maximum BIS/FIS extent and the Fladden Group formed beneath relatively stagnant ice while the WG ice stream was active a few kilometres to the south. Flow direction in the form of the MSGLs mapped by Graham et al. (2007), a lack of any external forcing (such as topographic control or an abrupt change in substrate) that would halt the progress of the ice stream in this locality, and the presence of numerate elongate bedforms consistent with ice streaming in the Fair Isle channel (Bradwell et al., 2008) discourage such a simplistic explanation and, rather, support the idea of an extensive ice stream at LGM maximum extent.

Bradwell et al. (2008) provide significant evidence that the extensive BIS/FIS ice sheet that extended over the northern North Sea during maximum LGM extent around 30 – 25 ka BP, with which the Fladden and Devil’s Hole tunnel valleys are associated with, disintegrated very quickly due to calving brought on by rising sea levels at around 24 ka BP. In their model, following maximum extent, a large marine embayment opened from the north, firstly extending just to the north of the Fladden Group, and then stretching southwards to the Witch Ground Basin; certainly inundating the Fladden Group tunnel valleys and most likely providing a minimum age for their incision (see Figure 8.9). Here, it is shown that the orientation and distribution of the Fladden Group tunnel valleys point to formation perpendicular to the part of the ice sheet retreating from the north-west, rather than from the embayment itself. Once retreat from maximum ice extent had begun the Witch Ground ice stream and associated convergence zone ceased to be active – ice sheet dynamics were instead centred on the rapidly opening embayment. The Devil’s Hole tunnel valleys could then originate from retreat centred on the southern Witch Ground Basin embayment, consistent with their northerly orientation and relatively narrow east-west spread. To the east, a lack of tunnel valleys and other significant seabed morphology indicating retreat is related to the dominance of the Norwegian Channel ice stream in Norwegian sector, still in evidence after the BIS break up (Sejrup, 1995, 2000, 2005).

8.2.3 Fladden Tunnel Valley Feature

A further point of interest in the Fladden Group is the kilometre scale feature present in the tunnel valley referred to as tv11 (for location see tv11 in Figure 8.2a). The feature
in tv11 is 66 metres high at its maximum and extends for approximately 9.12 km, as shown in Figure 8.10a. At its widest it almost fills the width of the tunnel valley at 2.3 km across, see Figure 8.10b and c. The feature is asymmetrical in cross section, and appears ‘mounded’ against the eastern wall of the tunnel valley with a semi-linear channel cutting its western slope. In profile the feature displays a steeper side to the south-east and gentler slope to the north-west.

Linear depositional landforms are commonly described within tunnel valleys in the North American literature (see Chapter 2.3.3 and Brennand and Shaw, 1994; Fisher et al., 2005) but tend towards crested esker morphologies, rather than this sub-elongate lobate feature. The feature in tv11 appears to sit unconformably within the tunnel valley (it does not follow the basal axis) indicating either: formation post initial excavation of the tunnel valley, or long-term modification of fill after formation, or, a combination of both. All scenarios cause some problems: for example, why would modern depositional processes favour the western flank when otherwise the tunnel valley base is fairly even from flank to flank along base? If the feature morphology reflects a steady depositional process, why the uneven cross profile? In other words, in an otherwise relatively flat seabed there is no indication of particular currents or other marine activity that would favour deposition centred around the eastern flank or a 9.2 km stretch in the centre of a 31 km long tunnel valley. Furthermore, if a Holocene (or at least post-tunnel valley formation) process was significant enough to provide such a large amount of sediment and focus it in such a small area, why are there no other similar features at the same scale? In short, it seems unlikely that a post-Weichselian marine process was responsible for such a large geomorphic feature in an otherwise fairly standard local environment. Unless there are a set of very particular currents operating in this 9 x 5 km² area, it is assumed that the feature is a result of glacially-influenced processes.

On initial observation, the feature most resembled the ‘toe’ of a valley-wall collapse – perhaps as a result of paraglacial relaxation of the valley walls, or periglacial free-thaw processes. However, there appear to be no fresh scars or scarps in the vicinity, or fans of a similar size in any of the other tunnel valleys nearby to support these ideas (note that there is evidence for smaller scale slope processes such as the apparent valley wall modifications seen in Feature A in Figure 8.6). Again, it is supposed that if this evidence for large-scale mass movement is not observed anywhere else in the nearby
Seabed tunnel valley systems (all incised into a fairly homogenous substrate, see Cameron et al., 1987), then it is unlikely to happen as an isolated occurrence in this particular tunnel valley, especially as the inherent properties of the tunnel valley which would lead to significant side-wall collapse (such as angle of repose, pore-space properties, or aspect (Abrahams, 1986) will be near-identical in the neighbouring seabed tunnel valleys. Finally, and perhaps most obviously, such a large scale feature resulting from mass movement would require a significant sediment source provided by headward retreat into the valley wall. There is no evidence for any retreat or lowering of the valley wall or seafloor at this point (location P in Figure 8.10d). Again, it seems likely that the feature was initiated at time of tunnel valley formation, when glacial and deglacial conditions provided a high-energy environment for landform creation as compared to the relative quiet of shallow marine conditions today.

The precise nature of such a formation process is elusive. It is worth bearing in mind that similar, but smaller, features may have been more pronounced and are now buried under a Holocene drape therefore concealing their presence (although thickness of any such drape is likely to be less than 11m (see Fyfe, 1983). Without subsurface data, it is difficult to ascertain whether the feature is a particularly large-scale remnant of a basal erosional sill formed by pressurised meltwater during tunnel valley formation or some kind of depositional feature such as the ‘beaded eskers’ discussed in Chapter 7.1 and observed within a few of the buried tunnel valleys.

In terms of the feature as an exaggerated version of the sills formed during subglacial formation, tv11 does display some of the most pronounced tunnel valley morphology of the seabed tunnel valleys. It is one of the longest, and contains the maximum widths and internal depths for all the Olex tunnel valleys. In particular, to the north of the feature, within tv11, an overdeepened reach of the tunnel valley is incised ~30m beneath average basal depth for approximately 5km (see Figure 8.10b). If the substrate at the point of the feature was particularly resistant to erosion, the deep to the north may be imagined as a ‘plunge pool’ feature where meltwater (either pressurised during formation, or subaerial post-formation) excavated a significant deep down-valley from the region of greater erosional resistance, and before returning to a more normal pattern of flow. However, the otherwise undulating base of tv11 and tunnel valleys in general preclude further expansion on this theory, relying as it does on gravitational potential.
and substrate homogeneity, both of which are unknowns in the pressurised subglacial meltwater formation situation for the tunnel valleys favoured in this work.

It is still possible that the feature in tv11 is a remnant feature representing some kind of impediment to flow, such as band of highly cohesive substrate, or a localised freezing or blockage of the subglacial meltwater passage. The narrow, deep channel to the west of the feature but still within the tunnel valley (well illustrated in Figure 8.10b) provides some evidence for flow post-feature formation in that it appears to cut down into the feature to a 'base level' c.220 m present consistently to the south of the feature. It appears flow diverted around the feature to the west, creating the asymmetric form observed today. Although it makes for an interesting discussion, the large-scale feature in tv11 was most likely formed during or very shortly after the formation of tv11 itself, and not by later depositional processes, for the reasons of location and uniqueness discussed above. It may be viewed as a particularly large example of the sills present in many works on tunnel valleys (see Chapter 2, and summary in O'Cofaigh 1996), possibly lowered in its western half by post-formation meltwater flow, although the reason for the initial large scale of the feature is unclear and there is no evidence for a subaerial channel within the rest of the tunnel valley. The feature is certainly unique amongst the 50 + seabed tunnel valleys examined in using the Olex dataset, and in the analysis of the 180 + buried tunnel valleys analysed in the rest of this work.

8.3 **Comparison with buried tunnel valleys**

8.3.1 **Data Comparison**

It is suggested here that the Fladden and Devil’s Hole Group channels measured above from the Olex dataset are tunnel valleys formed subglacially during the LGM. Towards the south of the cnsmerge dataset (see Figure 4.2) it is possible to find three tunnel valleys identified in both the 3D seismic reflection survey cnsmerge (Section 4.1.2) and in the Olex dataset. Figure 8.11a and b show the tunnel valleys as bathymetric deeps in the Olex dataset, and the same area in timeslice approximately 23m below seabed in the cnsmerge dataset. Figure 8.11c and d highlight the superior quality and resolution of the Olex dataset for analysing the seabed tunnel valleys in cross section, where an
Asymmetric profile is apparent and internal depth is resolvable. However, as shown in Figure 8.12, the 3D seismic datasets do allow for a good first order approximation of the geometry of the seabed tunnel valleys to be constructed in three dimensions, and provide a measure of confidence for descriptions and analyses of tunnel valley morphologies mapped on a lower resolution 3D seismic dataset.

Apart from this exercise in data comparison, what else can the seabed tunnel valleys measured in Olex tell us? Figure 8.13 compares the buried tunnel valley networks mapped in Chapter 6 of this work just a few kilometres to the south of the Fladden Group, constrained only by the limits of the 3D datasets (see Figure 4.2). It is very likely that these buried tunnel valleys extend north-east beneath the seabed features; therefore it is assumed that direct comparison can be made. However, it is important to note again that the buried tunnel valleys are found to be resolvable into a number of cross-cutting generations at local and regional scales (see Chapter 5.3), and it is in this framework that they are compared to the seabed tunnel valleys.

8.3.2 Morphology and Orientation

The Moray Firth and Fladden groups of seabed tunnel valleys exhibit smaller than average widths compared to the buried tunnel valleys, but still within the range of 1 to 2 km commonly found for the buried generations. Width to depth ratios are slightly higher than for the buried tunnel valleys, although this may result from a lack of resolution relating to the infill of the buried tunnel valleys meaning internal depth cannot always be accurately measured (i.e. see Chapter 7). No equivalent to the Generation 4 buried tunnel valleys, which display very large w:d measurements due to widths of up to 7 km were observed. Valley wall steepness measurements for the seabed tunnel valleys were on average less than those observed for the tunnel valleys (i.e. a maximum of 17° compared to 40° for the buried tunnel valleys) but this may again relate to more reliable measurements for morphology in the bathymetric dataset.

In terms of planform complexity, the seabed tunnel valleys display less evidence for high-angle bending and branching, and do not appear to show any anastomosing reaches. The seabed tunnel valleys also display a much greater degree of regularity in spacing, with tunnel valleys in the Fladden Group spaced at approximately 20 km intervals, and the Devil’s Hole Group at c. 15 km. No evidence was found in the seabed
tunnel valleys for hanging valley relationships, spillway features or other morphological features found in the buried tunnel valleys and described in Chapter 6.1.1.6.

A number of factors may account for these morphological differences: Firstly, a lack of reoccupation and modification following formation for the seabed tunnel valleys, and secondly, differences in the configuration and dynamics of the ice sheet(s) responsible for their formation.

The first point, highlighting the lack of post-formation modification experienced by the seabed tunnel valleys is the simplest to rationalize. The buried tunnel valleys are characterised by their separation into multiple cross-cutting generations, indicating their polygenetic origin as in Chapter 5. Chapter 6 of this work discusses the abundant evidence for reoccupation and modification of the buried tunnel valleys post-formation, with some younger generations seen clearly to follow the path of older tunnel valleys. The presence of 'hanging valleys', relict 'meander' bends, and some instances of bifurcation and anabranching in plan form are also indicative of reoccupation and modification over a number of tunnel valley generations (see also Lonergan et al., 2006, p.901). Subaerial fluvial systems within the buried tunnel valley infill (see Chapter 7), are used to infer a gap between formation and gradual fill, as well as the fact that tunnel valley morphologies may have been modified by processes outwith those relating to subglacial formation.

No evidence is found within the Fladden and Devil's Hole tunnel valleys for any fluvial-type channels (despite lateral dataset resolution being greater than that for the buried tunnel valleys), or for any significant mass movement or para/peri-glacial adjustment. It is clear in the case of the seabed tunnel valleys that they have experienced little post-formation modification, apart from a thin (ca. 11m) Holocene drape (Fyffe, 1983). The asymmetry of feature tv11, as discussed above, is most likely a result of processes active during subglacial formation, and did not appear to alter the form of the tunnel valley itself. From the dates summarised by Graham et al. (2006) and in Graham (2007) it is apparent that the Fladden and Devil's Hole Groups of tunnel valleys were incised during the LGM Weichselian glaciation of the North Sea at MIS 2, and not
reoccupied by any further advances or retreats, hence their geomorphological 'simplicity' as isolated, relatively straight depressions.

The relative simplicity and regular spacing of the seabed tunnel valleys have more in common with the morphology of Generation 1 tunnel valleys from the northern study area (see Chapters 5.3.3.1, 6.1.1.7) and those buried tunnel valleys in the southern study area in Dataset M. The results of Chapter 6 suggest that these buried tunnel valleys were influenced more by ice marginal directionality and drainage, which explains their relatively straightforward morphology. It is therefore considered here that the relative simplicity of the morphology of the valleys in the Fladden and Devil's Hole can also be partly accounted for by their formation in relation to a well-defined ice margin.

The most striking difference between the buried tunnel valleys and those at seabed in the Fladden Group is in preferred orientation. None of the seven regional generations of tunnel valleys in the northern study area located within 100 km of the Fladden Group and identified in Chapter 5.3 display comparable significant NNW/SSE orientations (see Chapter 6, Figure 6.16). Towards the south of the study area, within Dataset M, the majority of the buried tunnel valleys trend NW/SE but the closest seabed tunnel valleys to this region – the Devil's Hole Group trend N-S (see Figure 6.15).

From the discussion regarding ice sheet configuration during the LGM as related to the seabed tunnel valleys above, it is confirmed that seabed tunnel valleys formed during a period of extensive North Sea glaciation and were most likely influenced by a combination of British and Fennoscandian ice (Sejrup et al., 2000, 2005; Carr et al., 2006; Graham, 2007; Bradwell et al., 2008). However, the significant differences in orientation and morphology between the seabed tunnel valleys and the buried tunnel valleys indicates the dynamics of the LGM ice sheet were much different to those which initiated the excavation of the older tunnel valleys. Chapter 9 of this work suggests a number of possible ice sheet configurations which would account for the variation in morphology and form.

8.4 Conclusions

The Olex bathymetric dataset reveals a number of seabed tunnel channels in the North Sea which can be split into four groups based on their morphology and location. The
Moray Firth and Montrose Groups are found near to the coast of north-east Scotland while Devil’s Hole and Fladden Groups are located towards the centre of the central North Sea.

- Morphological analysis of all of the seabed channels reveal undulating basal profiles indicative of subglacial formation related to the last glacial maximum.
- All of the channels appear to start and end abruptly and display lengths up to 65 km. Average widths for the channels range between 1 and 2 km, with internal depths of up to 150 m observed in the Fladden Group.
- Overall, the Moray Firth and Montrose Groups display smaller cross-sectional morphologies and more complexity in planform. The Moray Firth Group displays an average E-W orientation, and the Montrose Group trends NNE-SSW, both parallel to the direction of the modern day coastline.
- The location of the Moray Firth and Montrose Groups of channels correspond to the proposed locations of BIS ice streams in the Moray Firth and Strathmore regions. It is suggested here that after the seabed channels formed along the paths of the former ice streams after they ceased to be active.
- The braided channels observed to the east of the Moray Firth Group are compared to proglacial bedrock systems and it is suggested they formed subaerially.
- The Fladden and Devil’s Hole groups of seabed channels are identified as tunnel valleys formed during the LGM. Their location is difficult to reconcile with respect to the BIS/FIS confluence proposed by Bradwell et al., (2008) and the evidence for the Witch Ground ice stream presented by Graham (2007).
- Rather than forming at the centre of a coalesced ice stream during LGM maximum extent, it is suggested that the Devil’s Hole and Fladden Group of tunnel valleys formed during retreat initiated by the initiation of a marine embayment from the north.

Comparison of the Fladden and Devil’s Hole Groups and the buried tunnel valleys investigated in Chapters 5, 6 and 7 of this work reveals a number of differences.

- The relative simplicity in morphology and planform of the seabed tunnel valleys results in part from their incision during only one glaciation, the LGM. A lack of
evidence for modification after formation, and for in-valley features such as hanging valleys and spillways supports this conclusion.

- Although they share a similar location, significant differences in orientation suggest that the configuration of the ice sheets which formed the buried tunnel valleys in the northern study area must have been significantly different than that of the LGM glaciation.

- The seabed tunnel valleys display much more regularity in orientation and spacing than the generations of buried tunnel valleys in the northern study area. The results of the rest of this work suggest that regular spacing and a lack of planform complexity in tunnel valleys are related to increased control by ice margin proximity or patterns of retreat. Thus, the seabed tunnel valleys appear to have experienced an overall control on their morphology and direction not apparent in the buried tunnel valleys in the northern study area.
Figure 8.1. Location map showing the bathymetry of the central North Sea imaged in the Olex dataset and the groups of seabed tunnel valleys referred to in the text.
Figure 8.2 Location and orientation measurements for (a) Fladden Group and (b) Devil's Hole Group of seabed tunnel valleys (for regional location see Figure 8.1). Note the circular features in (b) are data artefacts. (c) Profile along the line x-x' for the Fladden Group tunnel valleys and (d) for the Devil's Hole tunnel valleys.
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Figure 8.3 Location and orientation measurements for (a) Moray Firth Group (b) Montrose Group of seabed tunnel valleys (for regional location see Figure 8.1) (c) Profile along the line p-p' for the Moray Firth Group tunnel valleys and (d) along line q-q' for the Montrose tunnel valleys.
Figure 84 Cross sectional morphologies for all groups of seabed tunnel valleys shown to scale.
Figure 8.5 Longitudinal profiles for tunnel valleys in the Fladden Group measured from deepest part of base to shoulder. See Figure 6.5 for method.
Fig 8.6 Oblique view to the north-west from location A in Figure 5.2a showing the undulating basal relief and steep valley walls of a seabed tunnel valley in the Fladden Group. Note vertical exaggeration is x 8. Linear features on seabed are acquisition artefacts.
Figure 8.7 Comparison of (a) bedrock channels in Victoria Land, Antarctica and (b) Braided seabed channels (labelled BC) in the eastern part of the Moray Firth, North Sea, showing similarity in planform and dimension. Figure 8.7a taken from Lewis et al. (2006, p.514), location of Figure 8.7b is shown in Figure 8.3a.
Figure 8.8 Reconstruction of LGM ice flow (dashed lines) and central convergence zone (shaded) as proposed by Bradwell et al. (2008), with seabed tunnel valleys (orange). Arrows indicate the direction of MSGL orientations recorded by Graham et al., (2007) and used to confirm flow to the northwest. Figure modified from Bradwell et al., (2008, p15).
Figure 8.9. Configuration of BIS (shaded grey) during the final stages of LGM deglaciation with the location of the proposed initial (solid) and extensive (dashed) marine embayment prior to the break up of the coalesced BIS and FIS from Bradwell et al. (2008). Seabed tunnel valley are show in in orange, and the nearshore groups in blue. Proposed flow directions from the Moray Firth and Strathmore ice streams are included.
Figure 8.10 Morphological characteristics of lobate feature in tv11 (location in Figure 8.2a). See text for details.
8.11 a) Olex seafloor bathymetry showing tunnel valleys in Devil's Hole Group, (see Figure 8.2) with limits (dashed) of cnsmerge 3D seismic dataset coverage in the same area. (b) Seabed tunnel valleys as viewed in 3D seismic dataset cnsmerge at ~23m beneath seabed using v=1750 m/s. Circular feature to the northeast is data artefact. (c) Cross-profile x-x' of tunnel valley identified by Fyfe (1983) from 3D seismic dataset, location shown in (b). (d) Cross-section x-x' (location in a) of the same tunnel valley measured using the Olex dataset.
Figure 8.12 3D surfaces created for the seabed tunnel valleys show in Figure 8.11 from the cnsmerge dataset showing clear details of morphology despite the 100 m bin size.
Figure 8.13. Location map comparing the bathymetry of the central North Sea imaged in the Olex dataset, the seabed tunnel valleys (in red), the outlines of all of the buried tunnel valleys imaged in Datasets A to I (northern study area, in grey) and in the cnsmerge datasets (black outline) and in Dataset M to the south of the study area (in grey). Grey shaded boxes indicate the location of the northern study area and Dataset M as referred to in Chapter 5.
Chapter 9: Synthesis and Conclusions

9.1 Summary of Results

This chapter concludes that the most important result of this work is the discovery and extrapolation of cross-cutting relationships between the buried tunnel valleys at a regional scale greater than 100 x 100 km (see Figure 3.35). Although Lonergan et al. (2006), Jørgensen and Sandersen (2006), and Kristensen et al. (2008) describe a similar phenomenon at smaller scales, this work provides conclusive proof that the tunnel valleys of the central North Sea are preserved as palimpsest landforms, and analysis of their relationship to ice sheets and with regards to their formation must be considered within this context.

The extent of the 3D seismic reflection datasets utilised in this work also reveals significant differences in tunnel valley directionality and, to some extent, morphology, related to location. The results of comprehensive mapping for the tunnel valleys reveal a much stronger directionality for tunnel valleys in the southern part of the dataset compared to those in the north (i.e. see Figure 6.14). Significant differences in morphology and direction are also observed between the regional generations of tunnel valleys in the northern study area and to the south in Dataset M, and are discussed further with respect to formation processes and Pleistocene ice cover and duration below.

Uneven basal profiles observed within the majority of the 180+ tunnel valleys studied provide conclusive evidence of their formation by pressurised subglacial meltwater. Variation in cross-sectional morphologies (e.g. variations in w:d measurements) and complexity in planform displayed by many of the buried tunnel valleys indicate alteration and modification of the tunnel valleys during and after original incision, Morphological evidence for further modification post-formation (such as widening by glacial processes and fluvial channels within tunnel valley infill) also points to a composite origin for the buried tunnel valleys. The re-occupation of Generation 3.5 tunnel valleys by Generation 4 tunnel valley with significantly different morphologies suggests at least one episode where tunnel valleys were preserved in the landscape between episodes of tunnel valley incision.
Analysis of buried tunnel valley infill was constrained by previous studies which indicate the fill of tunnel valleys in north-west Europe to be characterised by complex, variable lithologies including gravels, sands and muds, not resolvable in the 3D seismic dataset used in this work. Some consistent seismic facies were identified within tunnel valley fill and used to imply infill during varying environmental conditions by a number of processes ranging from direct ice contact to quiet marine deposition. Fluvial channels and esker-type depositional features present within fill packages are also indicative of changing conditions over time during fill. Many tunnel valleys appear to have been completely infilled prior to incision by a younger generation, suggesting a complete cycle of subglacial erosion, fill and return to marine conditions prior to the onset of a new generation of tunnel valley incision.

Stratigraphic evidence confirms that tunnel valley tv1a (Figure 5.35, 5.27, 7.14, 7.15) is of pre-Elsterian age, as it is seen to incise from within the Aberdeen Ground Formation (unit I in seismostratigraphy of Graham, 2007), just below the horizon tied to Bruhnes-Matuyama reversal in BGS borehole 77/02 (MIS 19). This finding is the first piece of evidence to prove direct ice cover over the central North Sea during the Early-Mid Pleistocene, and is an important result of this work.

Analyses of seabed channels in the central North Sea as imaged in the Olex bathymetric dataset reveals two sets of channels related to the Last Glacial Maximum. Nearshore seabed channels are associated with drainage along the path of local ice streams during the final stages of deglaciation. Seabed channels observed offshore in the vicinity of the Witch Ground Basin are identified as tunnel valleys formed during the break up of the LGM triggered by the formation of the marine embayment proposed by Bradwell et al. (2008), and described in Figure 8.9.

9.2 Tunnel Valley generations and the glacial history of the central North Sea

In contrast to the more traditionally accepted 3-stage model of Mid to Late Pleistocene glaciations based on onshore evidence from north-west Europe (see summary in Ehlers, 2005), which are hampered by the erosional nature of each re-advance, this work finds
evidence for numerous episodes of ice cover in the central North Sea during the Pleistocene. The North Sea tunnel valleys studied here show clearly that Generations 2 to 7 incise from approximately the same stratigraphic level, proving that each episode of incision largely erodes the evidence of previous glaciations and interglacial deposition, apart from the large features (i.e. tunnel valleys) which incise beneath the ice-sheet base. However, the morphological insight afforded by the 3D seismic data allows the tunnel valleys to be separated by their cross-cutting morphology and patterning, therefore allowing individual episodes to be separated.

Based on observations of buried and surface tunnel valleys at the regional scale, up to nine episodes of Pleistocene tunnel valley formation within the central North Sea are identified. A single Early-Mid Pleistocene tunnel valley is found to be older than the Bruhnes-Matuyama reversal at MIS 19. Between MIS 19 and the onset of the Weichselian glaciations (MIS 5d), up to seven generations of tunnel valleys incision are identified (depending on whether Generations 3.5 and 4 are considered separately or together). Finally, a single set of tunnel valleys at seabed are considered to be Weichselian in age. Fill analysis in Chapter 7 indicates that a number of the tunnel valleys contain a well-layered upper fill indicating a return to marine conditions post-incision, and that many generations of tunnel valleys are seen to incise into completely filled older valleys, suggesting a full cycle of incision and fill between most episode of tunnel valley incision for Generations 2 through 7.

Marine and ice core records in the region also record multiple cold periods throughout the Pleistocene (see Funnell et al., 1995, Bradley, 1999) which can be directly correlated the episodes of tunnel valley incision described above, shown in Figure 9.1. The incision of tunnel valley tv1a would correspond to a cold stage recorded at MIS 22 or 20, while Generations 2 to 7 can be interpreted to relate to significant peaks at MIS 18, 16, 12, 10, 8 and 6. This association would mean that the eldest tunnel valleys (Generations 2, 3, 3.5 and 4) are pre-Elsterian. Tunnel valley tv1a provides the only direct evidence for pre Bruhnes-Matuyama ice cover in the central North Sea to date.

9.3 Relationship between tunnel valleys and Pleistocene ice sheets

Praeg (1996, 2003) showed clearly that that buried tunnel valleys in the southern North Sea were formed perpendicular to the nearby Elsterian ice margin at the time of
formation. Kristensen et al. (2007, p.809) assume that the tunnel valleys “drain down-ice ... to an ice sheet margin located in a general southward direction” related to the influence of ice moving SSW from the Norwegian highlands. However, the central North Sea area which is the focus of this work is notable for its distance from the generally accepted limits of Pleistocene ice sheets in the region (see Chapter 3; Figure 3.1). Figure 5.41 shows the relative position of the tunnel valleys investigated in this work and those of Praeg (1996; 2003), Lonergan et al. (2006) and Kristensen et al. (2007) with respect to the accepted limits of the Elsterian, Saalian and Weichselian glaciations of the North Sea according to Ehlers and Gibbard, (2004).

None of the currently accepted ice sheet limits (i.e. which trend roughly E-W across the southern North Sea and Germany and Denmark) would appear to result in a NE-SW trending system of tunnel valleys, as generally observed in the northern part of the study area, especially if the features are assumed to form perpendicular to the ice margin as suggested by Praeg (1996, 2003) and Kristensen et al., (2007) (i.e. see Figure 5.41, Ehlers and Gibbard, 2004). This argument leads to the conclusion (a) that the tunnel valleys in the northern part of the study area were formed perpendicular to a retreating ice sheet which extended significantly from either the Norwegian or northern British mainland (i.e. towards the NE or SW), or (b) were formed beneath the central part of an ice sheet and not dominated by margins some distance away.

9.3.1 Ice-Marginal Scenarios

The former scenario is similar to many recent models of the Weichselian glaciation (Figure 3.1; Figure 5.41; Sejrup, 1994, 2000; Carr, 2006; Graham, 2007; Graham et al., 2007; Bradwell et al., 2008) which depend on the build up of ice on the British and Scandinavian highlands which then converge to fully occupy the central North Sea, and eventually retreated backwards towards land during deglaciation. Tunnel valleys form parallel to the retreating margins. Usually, it is considered that an independent British Ice Sheet (BIS) extending into the North Sea would do so generally towards the northeast and that the influence of the Scandinavian Ice Sheet (SIS) would divert this flow towards the north and west (Bradwell et al., 2008). The areal coverage of the tunnel valleys in the northern part of the central North Sea revealed by the extensive datasets used in this work do confirm significant ice cover in the central North Sea during the pre-Weichselian glaciations, but do not comply with the above ideas regarding ice sheet
directions. This can be illustrated using the ice limits proposed by Lee et al. (2002) for a hypothetical MIS 16 and Elsterian glaciation as in Figure 9.2a (note that the positions of the southern margin of Lee et al.'s model are significantly different to the generally accepted margins for the Elsterian and Saalian as shown in the figure). Lee et al.'s suggested ice margins for the SIS and British ice sheets BIS are roughly consistent with the direction of the tunnel valleys observed in the work of Praeg (1996; 2003) and Kristensen et al. (2007) but the confluence between the SIS and BIS lies directly over a number the cross-cutting generations of tunnel valley analysed in the northern study area of this work. If the tunnel valleys in this work were formed during the break up of ice cover over the central North Sea in this kind of configuration (BIS and SIS retreat towards the southwest and northeast respectively), the resulting system of tunnel valleys would be expected to display the configuration shown in Figure 9.2b, where two sets of regularly spaced tunnel valleys have formed perpendicular to the two ice margins, separated by an area with minimal tunnel valley incision.

The above scenario is therefore refuted by the continuity of the buried tunnel valleys found in this area as well as the observation that the generations of buried tunnel valleys within the northern study area show significant differences in orientation – if these tunnel valleys were formed during the break up of the BIS and SIS over the central North Sea during deglaciation, they should all exhibit a similar NE-SW trending orientation. Significantly, no evidence was found in the study area to indicate that the separation of the two ice sheets initiated tunnel valley formation, for example, an 'initiation line' marking the start points of a parallel set of tunnel valleys.

Another ice-margin scenario places either the BIS or SIS as dominant, with the NE-SW trending tunnel valleys formed during the retreat of either a significant ice lobe, or from a convergence zone to west or east of the study area, as in Figure 9.2c, d and e. If the location of the convergence zone, or the relative dominance of the BIS and SIS varied between glaciations, the resultant build up of tunnel valleys related to each retreating ice margin could result in the cross-cutting generations imaged in this work, as in Figure 9.2e. However, as Figure 9.2e begins to demonstrate, the notion of strongly NNE-SSW trending tunnel valleys forming beneath a retreating ice margin raises some questions about the geometry of such a margin, whether originating from the BIS (as shown) or SIS, and given that the NNE-SSW trending tunnel valleys occur during a number of
generations, and very rarely in the southern part of the study area, the necessary conditions to produce this pattern seem unlikely to have been repeated.

However, to the south of the study area, in Dataset M, Generations 2M and 3M display a strongly preferred NW-SE orientation in contrast to those observed in the north. This tendency is generally reflected in the majority of tunnel valleys observed in the southern area (south of 57°30'N), which trend between NW-SE and NNW-SSE, suggesting a stronger control on direction during formation than for the northern area. A lack of datasets of comparable quality to those in the north prohibits extensive comparison, but in general, it is considered here that the tunnel valleys in the southern area were more heavily influenced by the southern margins of Pleistocene ice sheets which coalesced over the North Sea, perhaps at locations similar to the Weichselian ice limit for the southern North Sea proposed by Sejrup et al. (2005) in Figure 5.41. The variations of direction observed in the tunnel valleys in the southern study area in this work, and by Kristensen et al. (2007) c. 100 km to the east of Dataset M can be accounted for by the effect of local ice conditions, which were likely to be dominated by ice from the east and the effect of drainage from the Norwegian channel to the north, which contains evidence for the oldest glaciations of the North Sea at 1.1Ma B.P, highlighting its regional importance (Sejrup et al., 1995, 2000).

9.3.2 Alternative hypothesis: tunnel valley formation distal from ice margin

An alternative to the ice-margin hypotheses outlined above is that the cross-cutting generations of tunnel valleys observed in the northern part of the study area were formed some distance from the ice margin during shelf-wide glaciation(s) of the North Sea and controlled by accumulation centres and ice flow independent of ice margins. Ice doming in the central North Sea area would provide the hydrostatic head needed to drive the formation of tunnel valleys, and the changes in orientation and morphology between generations of tunnel valleys would reflect changing internal ice sheet configurations between glaciations, and in some cases (i.e. Generations 3.5 and 4), significant re-configuration, advance and retreat within glaciations (see Figure 6.17).

Ice domes may accumulate in response to subglacial topography and lithology, but are also discussed in terms of the instantaneous glacierisation and marine ice transgression hypotheses of Ives et al., (1975) and Hughes (1986) respectively. In these scenarios the
build up of large ice sheets respond to initial freezing which lowers albedo and reduces regional temperatures sufficiently to lower the snow-line and encourage the accumulation of ice which forms ice domes. Small (< 50 km across) ice domes create conditions favourable for snowfall as precipitation rates increase towards the summit (Benn and Evans, 1998). An irregular ice surface over the central North Sea area, controlled by a number of ice domes acting as accumulation centres could drive the formation of tunnel valleys as the build up of pressure encouraged ice movement and increased meltwater production away from the major domes. Sediment and meltwater evacuated by the tunnel valleys would be transported to areas of lower hydrostatic pressure before being reworked as the internal configuration of the ice sheet adjusted. Ice domes may also encourage ponding of meltwater, either in a depression beneath an ice dome or in depressions between ice highs (Nye, 1976; Dowdeswell, 2002). Recent work on ice sheet modelling such as that by Boulton and Hagdorn (2006) for the British Ice Sheet emphasise irregular, dynamic ice surfaces such as those proposed above.

Dynamic processes within ice sheets may also be relevant to tunnel valley formation. A number of recent works on the Weichselian glaciation of the North Sea have analysed evidence for ice flow directions in the central North Sea for BIS/SIS coalescence during the LGM and subsequent retreat (Graham et al., 2007; Graham, 2007; Bradwell et al., 2008). The results of these works indicate that drainage was focused upon a convergance zone in the central North Sea extending south-eastwards from the Fair Isle Channel, and ice flow was generally channelled towards the north-west. The LGM seabed tunnel valleys studied in this work (see Chapter 8; Figure 8.9) do bear similar NNW-SSE trending orientations in common with the proposed flow directions, providing evidence that ice streaming and/or flow during maximum glaciation may affect tunnel valley direction. However, Figure 9.3 compares these LGM flow directions to the location and dominant orientation of the buried tunnel valleys in the study area, where it is clear that the ice sheet configuration envisaged for the Late Weichselian maximum glaciation would not have resulted in the creation of the buried tunnel valleys which are the main focus of this work.

9.3.3 Conclusions on ice sheet configuration

The discussion of orientation and morphology above highlights the complexity of the tunnel valley systems found in this work. It must be emphasised that a number of
possible ice sheet configurations may result in the same pattern of tunnel valley as that observed, but the scenarios outlined above give an idea of some of the possibilities.

The morphological analysis of the buried tunnel valleys raises a number of points, the most significant of which is that the majority of the tunnel valleys, at least in the northern study area, appear to bear little relation in form or direction to any hypothesised ice sheet margin, and are therefore implied to have formed during extensive episodes of ice cover in the North Sea where the region was central to the ice sheet.

Buried tunnel valleys in the southern part of the dataset display a significantly more coherent orientation, and are considered to have been formed more proximal to ice margins. Both areas require a number of separate glaciations to account for the cross-cutting generations of tunnel valleys observed.

9.4 Future Work

The results of this study show that buried tunnel valleys are ubiquitous beneath the central North Sea and that the potential for further investigation is significant. Further mapping similar in nature to that carried out in this work using the top 1000 ms of comparable commercial 3D seismic datasets would allow the true extent of the features to be realised, and a continuation of the regional separation of cross-cutting generations to be carried out.

From the work of Lonergan et al. (2006) and Kristensen et al. (2007) it is also suggested that a relatively small decrease in bin spacing (i.e. from 25 m to 12.5 m) for the seismic datasets used to image the tunnel valleys would provide a better picture of the infill of the tunnel valleys within this work, and would not necessitate the acquisition of new seismic data if pre-existing datasets at the higher resolution can be found for similar locations.

Utilisation of high resolution 2D seismic data could also add significantly to the understanding of the tunnel valleys in this work if profiles overlapped with the 3D seismic datasets. Figure 7.14 provides an example of a high-resolution 2D seismic line from the mungo dataset towards the south-east of the study area (see Figure 3.1), which
shows excellent potential for the analysis of tunnel valley fill and morphology, but which is limited in its use with respect to the findings here if it cannot be correlated with the regional networks of tunnel valleys and its planform realised. The higher resolution data shown in Figure 7.14 generally agrees with the chaotic and dipping seismic facies identified Chapter 7, lending support to the interpretation from the lower-resolution 3D seismic data.

As discussed in Chapter 3.1, the glacial history of the central North Sea is poorly constrained due to a lack of chronological and genetic control for the glacigenic sequence of the region. In order to clarify the position of the buried tunnel valleys within a regional chronostratigraphy, improved dating is required. Although it may be the case that the cross-cutting complexity and time-transgressive modification evident for many of the tunnel valleys precludes accurate dating of their fill, targeted coring in the study area which concentrated on relatively isolated tunnel valleys strongly associated with individual generations would provide a rigorous constraint on the association of the tunnel valleys to the Pleistocene glaciations of the North Sea, and on the generational interpretation presented here.

Further work is also required to clarify the glaciological conditions required for tunnel valleys to form towards the centre of an extensive ice sheet, and what might affect their direction and morphology in such a situation. Recent modelling of the British Ice Sheet during the LGM indicate a dynamic, relatively thin ice sheet which was dominated by relatively short-lived periods of surging and ice streaming (Boulton and Hagdorn, 2006). The tunnel valleys mapped in this work would provide a significant addition to the extension of this model to account for incursion into the North Sea.

9.5 Conclusion

The results of this work fulfil the aims set out in Chapter 1.1 by providing detailed insight into the nature of the tunnel valleys, buried and at seabed, in the central North Sea. Key conclusions are detailed below.

- A major result of this work is the discovery and separation of up to eight cross-cutting generations of buried tunnel valleys at a regional scale (100 x 100 km) in the central North Sea.
- A single tunnel valley, tv1a, comprises the oldest generation of tunnel valleys identified in this work, and is found to predate the Bruhnes-Matuyama magnetic reversal. This tunnel valley provides the first piece of direct evidence for a pre-MIS 19 glaciation in the central North Sea and is correlated to the marine isotope record during a cold period at MIS 22.

- The seven younger buried generations of tunnel valleys correspond to seven peaks in the marine isotope record which indicate cold periods at MIS 18, 16, 12, 10, 8 and 6. It is therefore concluded that the tunnel valleys of the central North Sea record a much more complex glacial history for the North Sea than the current three-stage model and that significant ice sheets were present in the area earlier in the Mid-Pleistocene than is currently accepted.

- Analysis of the morphology and distribution of the buried tunnel valleys in the northern study area suggest their formation some distance from ice margin, possibly central to an ice mass dominated by multiple ice domes and an irregular surface which controlled hydrostatic drainage beneath the ice. Changes in ice build-up and internal configuration between glaciation account for the variation in form and direction between glaciations.

- Comparison of buried and seabed tunnel valleys reveal similarities in form, but differences in direction and distribution which suggest that the configuration of the LGM ice sheet was significantly different to any of the pre-Weichselian ice sheets responsible for the formation of the buried tunnel valleys.
Figure 9.1 Paleomagnetic history and global oxygen isotope record from 1.4 Ma B.P. to the present correlated to the marine isotope stages (MIS) and the generations of tunnel valleys separated within this work. Red circles mark the position of cold periods which can be related to Generations 1-7 (in red) of the buried tunnel valleys. Diagram modified from Funnel (1995).
Figure 9.2 (a-f) Models of tunnel valley formation in the northern study area related to ice sheet retreat based on the model by Lee et al (2002) shown in (a). Dashed red lines indicate prospective ice margins, solid black lines represent tunnel valleys. The traditional limits for the Anglian (orange) and Saalian (green) glaciations are taken from Ehlers and Gibbard (2004).
Figure 9.3 Reconstruction of LGM ice flow (dashed lined) and central convergence zone (shaded) as proposed by Bradwell et al. (2008). Red arrows indicate the direction of MSGL orientations recorded by Bradwell et al. (2007) and Graham et al. (2007) and used to confirm flow to the north-west. The location of the buried tunnel valleys mapped in this study and their the dominant orientations from the cross cutting generations in the northern study area and Dataset M are shown for comparison. Figure modified from Bradwell et al. (2008, p15).
References


Patterson, C.J., 1997. Southern Laurentide ice lobes were created by ice streams: Des Moines Lobe in Minnesota, USA. Sedimentary Geology, 111: 249-261.


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Appendix A: Notes on the acquisition of the 100 m bin merged dataset referred to in the thesis as cns merge.

The report reproduced below was produced by PGS Reservoirs and is intended to provide more information regarding the acquisition and processing of the merged dataset referred to by PGS as CNS MegaSurvey and in this thesis as cnsmerge. It is not the work of the author and is referenced as PGS Reservoirs (2005).

The CNS MegaSurvey is composed of data merged from more than 170 original 3D surveys.

The input data to merging are generally zero-phased, 3D final time migrated (released) data sets. Upon delivery from PetroBank™, the input data have been loaded onto the PGS processing system and initially were quality controlled by inline and crossline plots, amplitude and time slices. Laterally quality control has been achieved by using holoSeis™ to view and check inlines and crosslines.

Prior to rebinning all the datasets were resampled to 4 ms (where appropriate) and the maximum output data length was set to 7000 ms. A grid was derived for each survey based on the original processing CDP-X and CDP-Y information, then the data was interpolated to a 12.5 m x 12.5 m bin, if not already at this bin spacing. The data was then rebinned on to the master grid using a sinc interpolator. The rebinned data was then quality controlled by inline/crossline plots, time slices and interactive Tigress quality control. The base survey was the original PGS MC3D Quad 22-93 final migrated data.

Data quality can vary from survey to survey, and occasionally it was necessary to clean up the input data prior to merging, thereby avoiding mis-stacking when the final merge was applied. The philosophy was to try and keep as much as possible of the original data character, whilst maintaining the overall quality of the final product. Where deemed appropriate, a mild FX deconvolution or TVF was applied to remove noise in the deeper section, and occasionally a K-notch filter was applied to clean up any shallow jitter. Once the noisier surveys were filtered, merge testing was carried out.

The original testing performed in Autumn 1999 showed that phase matching via cross-equalisation produced a good match when tested on isolated surveys, but it was decided this route could introduce problems when trying to match many surveys together. Furthermore, it was decided that the original phase of the input data should be retained, wherever possible, to allow continuity to existing interpretations and well ties that have already been made by data owners. This procedure has been followed for the UKCS data only, whereas phase matching has now been applied to all surveys from the Norwegian and Danish sectors.

In the majority of cases in the UKCS, only a static correction and amplitude match is used for the merging; this technique having also been demonstrated to produce a good match. Exceptionally, a few surveys are input as raw migration datasets - these required post migration processing (TVF and gain) followed by phase and amplitude matching using cross-equalisation.

For each survey input to the merge:

- Data polarity tests have been carried out on all surveys using a comparison of wavelets derived from seismic data with wavelets derived from corresponding well data,
where available. This process has been determined to be an extremely valuable and worthwhile test, due both to the inconsistency of the polarity conventions of the input datasets, and to the uncertainties in achieving good geological correlation over some parts of the CNS area. Nominal output polarity convention is Reverse SEG – an increase in acoustic impedance produces a negative number on tape and is represented as a trough in profile.

- Static analysis was carried out by cross-correlation of an overlapping region, with the lowest possible static being chosen.
- Amplitude analysis was carried out on overlapping data, picking a wide range of CDPs to sample the amplitude range as broadly as possible. The amplitudes were measured over sliding gates of 400 ms, with an overlap of 200 ms, over a time window of 200 - 7000 ms. A match gain curve was then derived by using a five point polynomial smoothing filter. Finally an AGC scalar is applied using a 1000 ms gate before ramp merging over nominally 40 traces (500 m). This overlap can vary depending on survey boundaries. The quality of each merge was checked by viewing inlines / crosslines across the merged area and generating time slice tests.
- Survey boundary merging is carried out firstly by contouring to define the optimum merge locations with overlap zones, then by ramp merging over nominally 40 traces (500 m) across these boundaries. The quality of boundary zone merges can vary considerably depending on fold, aperture, vintage, processing applied, etc., although contouring allows prioritisation of good data to the exclusion of any poorer data. Final merge quality is checked by interactive holoSeis™ QC, with spatial QC performed by output of UKOOA datasets and timeslices.

In terms of resolution, in the ER Mapper QC'ing of data interpretation, PGS can, with the right data conditions, resolve interpretation QC issues down to 4 ms offset (1 sample). Obviously this is relative resolution and in exceptional situations, but it does suggest that geological discontinuities of 8-12 ms should be recognisable, providing the data quality is reasonable.

Lateral resolution is also complex. It will depend mainly on the bin spacing and orientation of the original surveys. The interpolation to 12.5 m prior to rotation should avoid aliasing effects during rebinning for older surveys, but may affect more modern (12.5 m, 16.67 m bin) surveys which are oblique to the MegaSurvey master grid. Once rebinned at 12.5 m, there is an obvious reduction in resolution with resampling to the 50 m or 100 m bin working datasets (i.e. those used in this thesis). For the most modern surveys (originally with bins ≤25 m), the main control on resolution will be the final, 50 m dataset, but with the few older surveys (bins 30 – 160 m), the original acquisition parameters will be more important.