

Plio-Pleistocene scour hollows in the Southern Bight of the North Sea

A.C. Liu,¹ M. De Batist,² J.P. Henriët³ & T. Missiaen²

¹Ningbo Oceanographical Survey, SOA, P.O. Box 75, Ningbo 315040, P.R. China; ²Renard Centre of Marine Geology (RCMG), Universiteit Gent, Krijgslaan 281 S8, B-9000 Gent, Belgium; ³Département des Géosciences Marines, IFREMER – Centre de Brest, B.P. 70, F-29280 Plouzané, France

Received 22 April 1992; accepted in revised form 21 November 1992

Key words: Eemian, high resolution seismics, paleomorphology, Quaternary

Abstract

Scour hollows in the Belgian and French sectors of the North Sea have been studied from seismic records and borehole data. These hollows are thought to have formed by tidal scouring and fluvial erosion, as there is no evidence of any formed by subglacial scouring. The Murray Pit is filled by Neogene sediments and was probably eroded during the Early Pliocene. The remainder of the hollows are incised into the top of the Paleogene, and occur essentially within fluvial paleovalleys. They were most likely formed during phases of Late Pleistocene sea-level rise and most have been filled by Late Pleistocene marine sediments.

Introduction

Seismic profiling has been used to investigate the geology of the Southern Bight of the North Sea since the 1960s. Houbolt (1968) and Laban & Schüttenhelm (1981) used sparker and 3.5 kHz profiles to study the morphology and internal structure of its many Holocene tidal sand banks. In the southern Dutch sector, Oele (1971) correlated his seismic interpretation with land observations to show the presence of some glacial deposits and ice-pushed ridges. Kirby & Oele (1975) described a shallow, filled basin in the French part of the North Sea. More recent surveys of the Southern Bight have concentrated on mapping the Tertiary and Early Pleistocene geology of the area (Cameron et al. 1987, Balson & D'Olier 1988, Henriët et al. 1989, De Batist 1989).

Recently Liu (1990) and Liu et al. (1992) presented the interpretation of a dense network of high resolution reflection seismic profiles across the Belgian and French sectors of the North Sea (Fig. 1),

which were acquired by the Renard Centre of Marine Geology (RCMG) at the University of Ghent. This yielded a detailed insight into the topography of the erosion surface separating Tertiary from overlying Late Pleistocene and Holocene sediments. During these investigations a number of scour hollows had been identified, most of them incised into the top of the Tertiary. Their origin is the subject of the present study.

Elsewhere in the North Sea, outside the Southern Bight, the observed closed linear sea-bed depressions, for example offshore the Humber Estuary, and the swarms of filled paleovalleys that were eroded during the Elsterian, Saalian and Weichselian glaciations, have been collectively referred to as 'incisions' by Wingfield (1990). Early research (Donovan 1973) suggested that these sea-bed depressions could have formed by subglacial stream erosion and/or tidal scour. Wingfield (1990) attributed both the depressions and the paleovalleys to erosion under or at the tidewater margins of the ice sheets that extended over large parts of the North

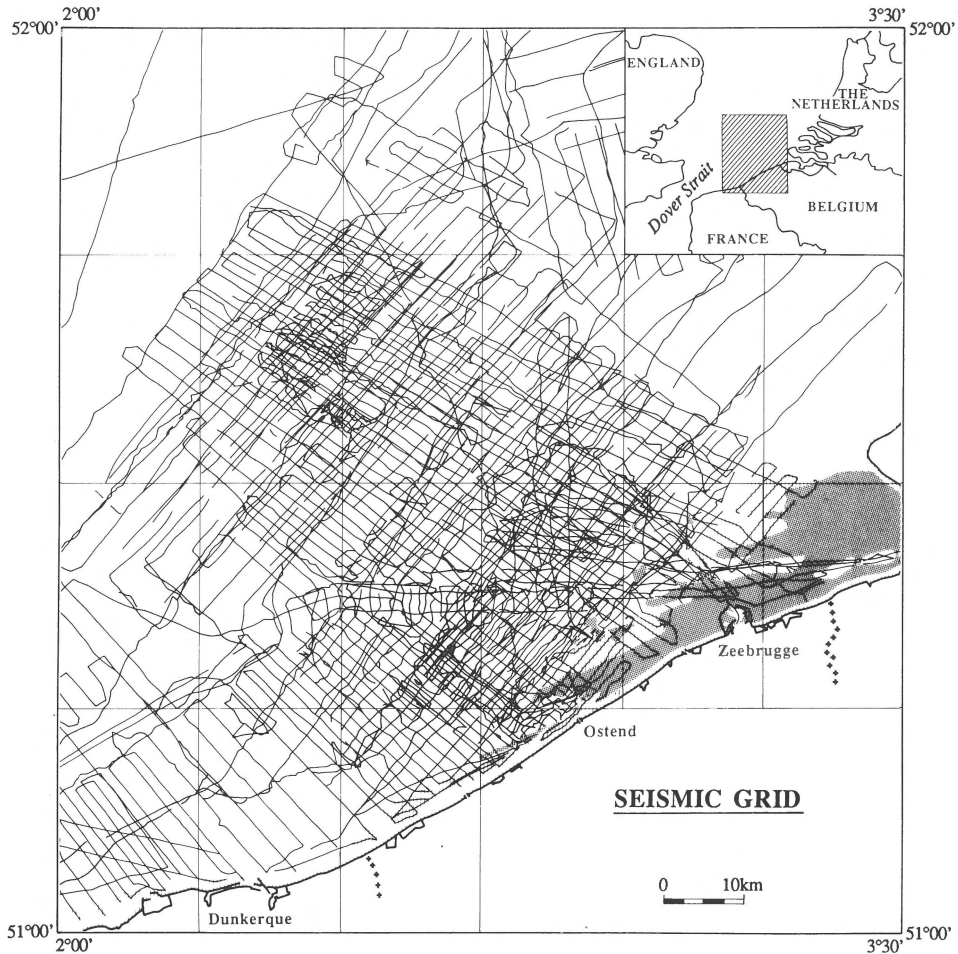


Fig. 1. RCMG's seismic grid covering the studied area (after Liu et al. 1992). The seismic data in the dark and light shaded areas nearshore are of poor quality due to acoustic blanking and sea-floor multiple interference respectively.

Sea during each of these three glaciations. This phenomenon, however, is not very likely to occur in the more shallow areas of the North Sea.

The paleovalleys are often up to 5 km wide and 30 km long, and their incised depths are commonly greater than 100 m, with a maximum recorded depth of 360 m (Wingfield 1990). They were mainly scoured into un lithified Pleistocene or Tertiary sediments, but locally they were eroded into bed-rock ranging from Precambrian to Mesozoic in age. Most of these glacial paleovalleys have been filled; others have been kept open, probably by tidal scour.

The scour hollows described in this paper are considerably smaller in scale, but more importantly,

they occur in an area which lies several tens of kilometres beyond the maximum extent of the ice cover in the North Sea area (Wingfield 1990, Joon et al. 1990). Therefore, an alternative explanation must be sought for the origin of these scour hollows.

Geological setting and Quaternary stratigraphy

The described area is located above the crest of the London-Brabant Massif, a structural high delineating the southern margin of the North Sea Basin during most of its geological history (Ziegler 1981, Henri et al. 1989). It is a key area, both for recording

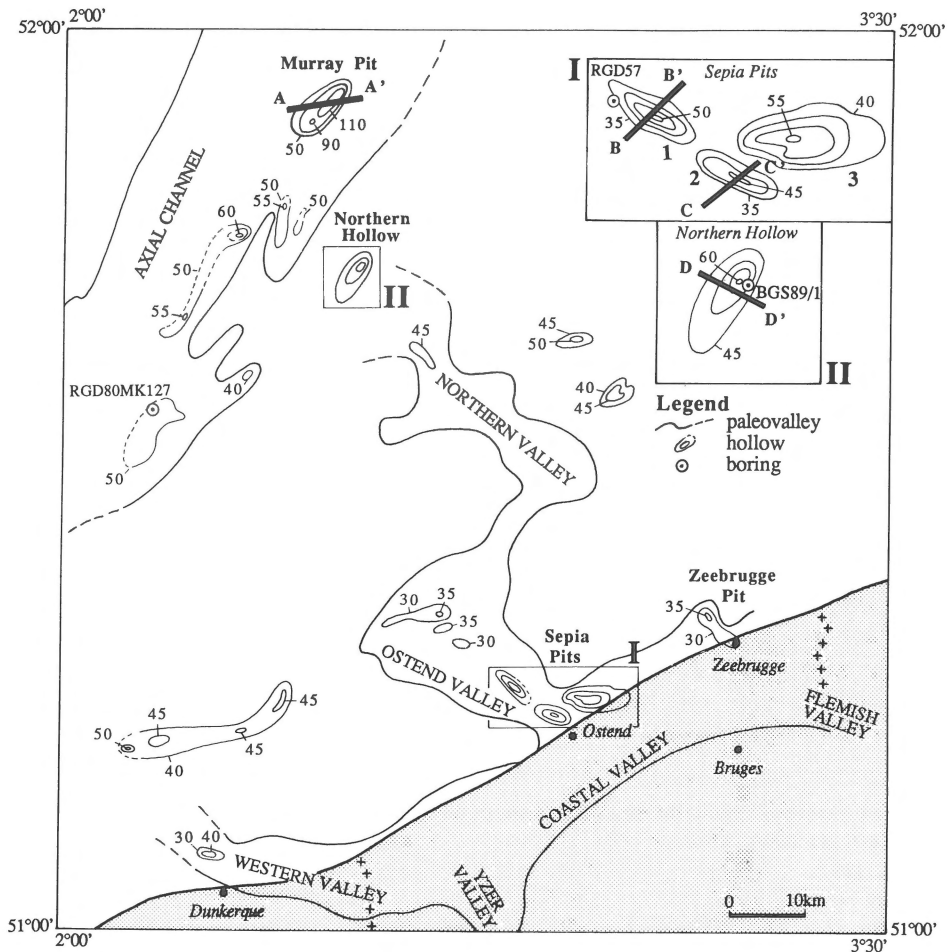


Fig. 2. Map showing the distribution of scour hollows and paleovalleys. The contours are in metres below mean lowest low water level at spring tide (modified after Liu 1990, Liu et al. 1992 and Mostaert et al. 1989).

the opening of the Dover Strait (Fig. 1) and for determining the southern limit of Quaternary glaciation in the North Sea.

All scour hollows and paleovalleys have been cut into Paleogene substratum, of which the detailed stratigraphy has been defined by seismic studies integrated with land geology (Henriet et al. 1989, De Batist 1989). This substratum is dipping towards the northeast, as it was tilted during the Neogene and Quaternary subsidence in the North Sea. It is truncated by a sharp erosion surface and overlain by Quaternary deposits. Neogene sediments are generally lacking offshore Belgium, but local occurrences have been reported from the extreme north of the studied area, where they occur as the infill of

a major scour hollow (Balson 1989, De Batist 1989, Mostaert et al. 1989).

The Quaternary deposits are generally thin offshore: they range in thickness from a few metres to 50 m. Locally, Tertiary strata are exposed at the seabed. Early Pleistocene deposits are entirely absent. Where they occur onshore, around Antwerp and near the Dutch-Belgian border, they consist of alternating intertidal and continental deposits (Paeppe et al. 1981). During the Early Pleistocene, the southern margin of the North Sea was located close to the north of the studied area.

Middle Pleistocene deposits (marine Herzelee Formation) of Cromerian-Holsteinian age are known from the coastal area near the Belgian-

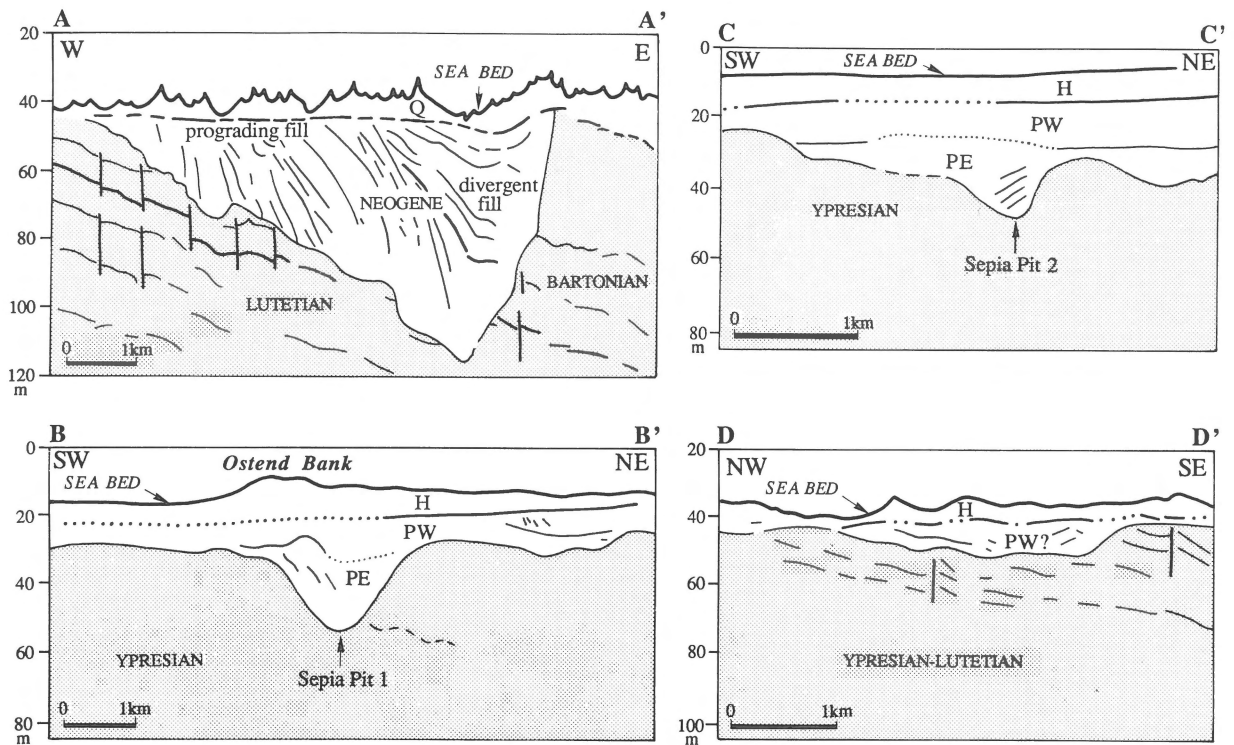


Fig. 3. Line-drawn interpretation of seismic profiles across some of the scour hollows. Location of profiles in Fig. 2.

A: Murray Pit (after De Batist 1989),

B: Sepia Pit 1 (after Liu 1990),

C: Sepia Pit 2 (after Liu 1990),

D: Northern Hollow (after Liu 1990).

Full or broken lines indicate observed reflectors (heavier lines denoting unconformities). Dotted lines indicate inferred contacts (approximate) in areas of poor seismic data quality. Q = Quaternary, H = Holocene, PW = Weichselian, PE = Eemian. Depths are in metres below datum of Fig. 2.

French border (Sommé 1979, Paepe et al. 1981). Such deposits, however, are thought to be absent offshore, where the Tertiary substratum is directly overlain by marine, Late Pleistocene (Eemian) sediments, reaching 9m in thickness (Kirby & Oele 1975). On the basis of the occurrence of mollusc species indicating cool to cold climatic conditions, Oele & Schüttenhelm (1979) suggested that these sediments could also be Late Saalian, but this is now considered unlikely as the presence of Eemian deposits has been proved along the coasts, both on land and offshore, in the southeast of the studied area (Paepe et al. 1981, Spaink & Sliggers 1979, Spaink 1981, Mostaert & De Moor 1989). Holocene deposits occur mainly in the form of tidal sand banks, which are up to 30m in amplitude.

Only a limited number of boreholes, with a maximum length of 10m, have been drilled. They are mainly located in the coastal part of the studied area, and only sporadically they completely penetrate the Quaternary. Quite recently, however, in the framework of the Southern North Sea Project 'Quaternary Geology', funded by the European Community, a borehole BGS 89/1 was drilled (Fig. 2) to 36m depth in the northern part of the studied area, reaching the Tertiary substratum at 24m below sea-bed (Maenhaut van Lemberge 1991).

Morphology at the top of the Tertiary

In general, the erosion surface cutting across the

top of the Tertiary, slopes northwestwards, from about 15m nearshore to 55m or more below sea-level in the northernmost part of the area. The most pronounced morphological elements of this erosion surface, however, are the major paleovalleys (Fig. 2), which were described by Mostaert et al. (1989), Liu (1990) and Liu et al. (1992).

The 'Coastal Valley', with an incised depth of 10m, lies below the present-day Belgian coast and has a maximum depth of 25m below sea-level. It joins the 'Flemish Valley', the course of which is well-known from onshore Quaternary sections, near the Dutch-Belgian border and the 'Yzer Valley' near the Belgian-French border. Offshore France, the Coastal Valley turns NW, and is referred to as the 'Western Valley'. Near Ostend, the valley joins the 'Ostend Valley', which extends further offshore into the 'Northern Valley' (Fig. 2).

Nearshore, the top of the Tertiary occurs as a platform which is transected by the Ostend Valley. This platform is separated from another platform at 30m below sea-level by a northwest-facing slope. A third platform occurs further to the northwest at 35m below sea-level. The bottom of the Quaternary basin in the Sandettie-Fairy Bank area off the Belgian-French border described by Kirby & Oele (1975), is probably an integral part of this 35m platform, which deepens further offshore into a major NE-SW aligned paleovalley, 'the Axial Channel' (Mostaert et al. 1989, Liu 1990, Liu et al. 1992). This Axial Channel forms the northern part of the Loubourg Channel, which extends from Dover Strait well into the Southern Bight of the North Sea.

Scour hollows

The observed scour hollows are located mainly within the paleovalleys. Their long axes are parallel to the valley in which they occur. The scour hollows situated further offshore seem to be deeper than those nearshore, with the exception of those in the Ostend Valley. The maximum depth of the hollows created during the Quaternary is 60m below present sea-level; one of the hollows of supposed pre-Quaternary age reaches much greater depths.

Scour hollows within the Axial Channel

The so-called 'Murray Pit' (after R.V. 'John Murray'), located in the northernmost part of the Axial Channel, is aligned NE-SW and has an elliptical shape (Fig. 2). It is about 10km long and 4km wide and has been scoured into Bartonian clays and Lutetian sands. The pit has a depth of 110m below sea-level, with an incised depth of 70m (Fig. 3A). It is the deepest scour hollow in the studied area.

The distribution of other hollows in the Axial Channel is not very clear, as the available profiles are confined to the channel's southeastern margin. All scour hollows mapped in this part are parallel to the channel axis, and have a maximum depth of 60m below sea-level, 10–20m below the base of the channel. These scour hollows have been eroded into Ypresian clays and/or the Ypresian-Lutetian transition sequence (Henriet et al. 1989, De Batist 1989), and their outlines coincide with the 50m depth contour (Fig. 2).

Bridgland & D'Olier (1989) contoured the bedrock surface in the wider Thames Estuary area. They identified two depressions within the Axial Channel, one coinciding with the Murray Pit, and the other representing the group of shallower scour hollows to the southwest of that pit.

Scour hollows within the Ostend Valley

The nearshore part of the Ostend Valley contains the so-called 'Sepia Pits 1, 2 and 3' (after R.V. 'Sepia'; Mostaert et al. 1989, Liu 1990). Each has a depth of about 50m below sea-level (Fig. 2) and has thus been cut 20m or more below the valley base. All three hollows have been filled completely by Quaternary sediments.

Sepia Pits 1 and 2 are incised into the uppermost part of the Ypresian clay, whereas Sepia Pit 3 is eroded into the Ypresian-Lutetian transition sequence. Sepia Pit 1 has a V-shaped profile and is buried beneath the Ostend Bank (Fig. 3B). Sepia Pit 2 is located further landward and has a somewhat irregular profile (Fig. 3C). The western margin of Sepia Pit 3 is steep and uneven, while the shape of its eastern margin is masked on seismic

profiles by a strong sea-bed multiple and by acoustic blanking due to gaseous sediments just below the sea-floor.

To the northwest of the Sepia Pits, in the offshore part of the Ostend Valley, a number of 5–10m-deep hollows are cut into the Ypresian clay (Fig. 2). These hollows are U-shaped in cross-section, having steep walls and flat bases, and are partly overlain by the Kwinte Bank.

Other hollows

Another scour hollow, here designated as the 'Northern Hollow', has been identified within the Northern Valley (Fig. 2). The hollow, with an incised depth of 15m, is cut into the Ypresian-Lutetian transition sequence and the Lutetian sands, and is asymmetric in profile. Its gentle northwestern flank is formed by a bedding surface of the Tertiary substrata. The base of the hollow clearly follows cuesta-like swells on the seismic records (Fig. 3D). This may indicate differential erosion of relatively soft substrata.

The 'Zeebrugge Pit', offshore Zeebrugge, is located at the eastern end of the Coastal Valley (Fig. 2). It is defined by the 25m depth contour and has been cut 10m below the valley base. This elongated hollow trends NW-SE and has been eroded into a sandy Lutetian sequence (Mostaert et al. 1989). Its northern flank is rather steep (min. 14%), and has been scoured into Bartonian clay, whereas its southern flank is very gentle (max. 4%) and rests on resistant calcareous sandstone beds of the Lutetian (Henriet et al. 1978).

The remainder of the hollows are relatively small and shallow, having been mostly scoured into platforms. Little information is available about their infill and they are not further discussed in this paper.

Infilling of the hollows

Axial Channel

The Axial Channel has only a thin and patchy cover of Quaternary sediments. All of its scour hollows

are filled, but outside these hollows the cover of Quaternary sediments has been largely removed due to strong tidal currents.

Within the Murray Pit, at least two stages of infill can be identified on the seismic records (Fig. 3A). Most of this infill is characterised by eastward-dipping reflectors ('prograding fill'), suggesting that the pit could have been filled by an influx of sediments from the west. If the pit was completely filled at this first stage, then it probably has been partly eroded subsequently, as a secondary valley seems to be present on its eastern margin indicated by an unconformity above which a divergent fill facies can be observed.

Cores taken from the uppermost part of the infill of the Murray Pit consist of glauconitic, muddy sands. Their foraminifera content indicates Early Pliocene, equivalent to the Luchtbal sands in Belgium and the lower part of the cross-stratified Coralline Crag in England (Balson 1989).

An 8m borehole (RGD 80MK127) in the southernmost scour hollow of the Axial Channel (Fig. 2), shows the occurrence of mainly coarse sands. Mollusc analysis indicates that the upper 4m comprise marine Holocene whereas the lower 4m are interpreted to be Late Pleistocene (Spaink 1981). The Pleistocene fauna contains, besides marine species, also continental species indicating temperate to temperate/warm climates, e.g. *Corbicula fluminalis*, which is not found in sediments older than Eemian. These molluscs are believed to have been brought into the area by a fluvial system. The borehole was terminated at 50m below sea-level, at or just above the erosion surface at the top of the Tertiary.

The infill of the Murray Pit clearly differs from that of the other hollows in the Axial Channel. The fills of these smaller scour hollows show only a few horizontal or subhorizontal reflectors, and rare, if any, foresets.

Ostend Valley

Borehole RGD57 has been drilled between 10 and 12m below sea-bed, just west of Sepia Pit 1 (Fig. 2). In cores from this borehole, the sediments are en-

tirely Late Holocene (Spaink & Sliggers 1979). As the Quaternary in this area is up to 50m thick (Fig. 3B), the borehole did not penetrate the complete infill of the Sepia Pits.

Nearby, at Bruges in Belgium, the Eocene is directly overlain by marine Eemian sediments, and by Weichselian and Holocene deposits. It is believed that during the Eemian transgression, the Tertiary strata in this area were extensively eroded by tidal currents to between 7 and 20m below present sea-level (Mostaert & De Moor 1989). Thus, Eemian and Weichselian may also be present in the near-shore part of the Ostend Valley beneath the Holocene.

Horizontal or subhorizontal reflectors have been observed at two different levels within the Quaternary sediments of the Ostend Valley, indicating a minimum of three different stages of infill. The lower seismic reflector occurs 25–27m below sea-level. In Sepia Pits 1 and 2, as well as in the northwestern hollows, this reflector is at the same level as the floor of the Ostend Valley (Figs 3B, 3C). The upper reflector is 15–20m deep, has a higher amplitude, and can be identified over a wide area in the Ostend Valley (Figs 3B, 3C).

Taking the borehole data into account, a Holocene age is proposed for the sediments above the upper reflector, Eemian for those below the lower reflector, and Weichselian for the intervening sediments. These three Late Quaternary units have also been recorded elsewhere in the studied area (Kirby & Oele 1975, Henriët et al. 1978, Mostaert & De Moor 1989).

On the seismic records, the sediments within the upper infill of Sepia Pit 1 dip north (Fig. 3B). Conversely, the basal sediments of the Sepia Pit 2 dip towards the southeast (Fig. 3C). It is therefore inferred that the infill of the Sepia Pits took place in two stages. From borehole data and seismic evidence, the sedimentary infill of Sepia Pit 3 seems to be similar to that of Sepia Pit 2.

Other hollows

Three stages of infill have also been observed in the Zeebrugge Pit. These have been inferred to be of

Eemian, Weichselian and Middle Holocene age (Henriët et al. 1978).

Borehole BGS89/1, drilled within the Northern Hollow, showed that 9m of Holocene, fine to coarse-grained, shelly marine sands overlie 15m of finer-grained, fluvial sand (with plant fragments) of possibly Weichselian age (Maenhaut van Lemberge 1991), a succession that was predicted from the seismic interpretation (Fig. 3D; Liu 1990, Liu et al. 1992).

Origin of scour hollows, discussion

As reviewed in the introduction, the formation of most of the paleovalleys in the North Sea has been attributed to scouring during glaciation, either subglacially (Donovan 1973, Destombes et al. 1975, Cameron et al. 1987, Joon et al. 1990) or by ice or marginal meltwater (Oele 1971, Oele & Schüttenhelm 1979, Wingfield 1990, Joon et al. 1990). Belgium and its offshore area, however, probably lay many tens of kilometres beyond the limits of glaciation in the North Sea area (Cameron et al. 1987, Joon et al. 1990).

The controversial views of Kellaway et al. (1975) and Destombes et al. (1975), who suggested that ice sheets may have penetrated from the English Channel through the Dover Strait into the Southern Bight of the North Sea during the maximum of the Saalian glaciation, have been refuted by Kirby & Oele (1975), Spaink & Sliggers (1979), Sommé (1979), Spaink (1981), Paepe et al. (1981) and Mostaert & De Moor (1989). No glacial deposits have been reported from Belgium or its offshore area, and there are no ice-pushed ridges like those associated with the Saalian glaciation in the Dutch sector (Oele 1971, Oele & Schüttenhelm 1979). Unlike the paleovalleys of the North Sea, the scour hollows in the Southern Bight have not been filled by fluvio-glacial or glaciomarine deposits. A non-glacial origin seems therefore more likely for these hollows.

Almost all of the Southern Bight scour hollows occur within clearly-defined paleovalleys. West of the Dover Strait, Smith (1985) has mapped systems of fluvial paleovalleys that drained westward across the English Channel towards the Atlantic Ocean.

Some of these valleys contain deep scour hollows, which Smith (1985) interpreted as plunge pools, formed by catastrophic breaching of the Dover Strait land barrier by ice-dammed water during one of the major glaciations in the North Sea. The Southern Bight scour hollows probably did not originate as plunge pools, as they occur on the opposite northeastern side of this land barrier. Nevertheless, the Northern Hollow was most likely scoured by rivers, as it has been filled by fluvial sediments (Maenhaut van Lemberge 1991). Severe fluvial scour has been recorded in Belgium within the Flemish Valley (De Moor 1988), where it occurred during the Saalian glacial stage. This indicates that the Northern Hollow, as well as the entire Northern Valley system, could well have been fluvially eroded during a glacial – possibly Weichselian (Maenhaut van Lemberge 1991) – stage, as a response to the important base level fall and constrained by sharp contrasts in bed-rock lithology.

Donovan (1973) and Thomson & Eden (1977) suggested that tidal scour may have been a factor in preventing sedimentation in some of the sea-bed depressions in the modern floor of the North Sea. Within the studied area, the Murray Pit was the only scour hollow to have formed before the Pleistocene. It could have been eroded by tidal scour, as at least the upper part of its infill comprises (Early Pliocene) marine, shelly sands. However, as this scour hollow was eroded down to 70m below the base of the Axial Channel, which itself was initiated as a fluvial paleovalley during the Middle Eocene (Balson & D'Olier 1988), a fluvial origin for the Murray Pit cannot be excluded.

Most of the area offshore Belgium has been dry land since earliest Pleistocene times. Temporarily, some marine sedimentation took place in the southwest of the studied area during Middle Pleistocene interglacial stages (Sommé 1979, Paepe et al. 1981), but it has only been during the last interglacials of the Eemian and Holocene that the whole of the area has been fully submerged (Kirby & Oele 1975, Spaink & Sliggers 1979, Mostaert & De Moor 1989). Thus, tidal scour can only be considered as a potential eroding mechanism during these (interglacial) periods of total submersion, while fluvial erosion is

more likely to have occurred during the Weichselian or Saalian glacial periods.

Within the Axial Channel, the scour hollows south of the Murray Pit have been filled by marine Eemian and Holocene (Spaink 1981). This indicates that these hollows were most likely formed by tidal currents in the early phase of the Eemian transgression.

Within the Ostend Valley, it is now known that fluvial erosion during the Weichselian glacial stage was unable to remove completely the marine Eemian deposits. Similarly, erosion during the Holocene transgression has not completely removed the Weichselian fluvial sediments that were deposited on top of these Eemian sediments (Mostaert & De Moor 1989). The same relationship has also been observed in the Sandettie-Fairy Bank area (Kirby & Oele 1975) and offshore Zeebrugge (Henriet et al. 1978), and may apply to most of the paleovalleys in the studied area.

Seismic interpretation suggests that the U-shaped scour hollows which occur in the offshore part of the Ostend Valley were filled by Eemian marine sediments. These hollows were most likely eroded by tidal currents during the Eemian transgression. Such an origin and age are also likely for the Zeebrugge Pit, which has a comparable morphology and an infill of similar seismic character.

Conclusions

Scour hollows in the Southern Bight of the North Sea are mainly incised through the top of the Tertiary. They are rather small, with the exception of the Murray Pit (10×4 km), and they are definitely much smaller than the ice-incised or subglacially eroded depressions of the North Sea. Most of the major hollows occur within paleovalleys.

The Murray Pit was scoured into the Axial Channel during the Neogene, most likely during the Early Pliocene, and could have had a fluvial as well as a tidal origin.

The Northern Hollow, located in the Northern Valley, was initiated by fluvial erosion, possibly during the Weichselian. Most of the other hollows were

probably formed by tidal scour during the early stages of the Eemian transgression when the sea invaded the studied area along pre-existing fluvial valleys.

The scale of the scour hollows is indicative of the intensity of Quaternary erosion. The maximum depth of this erosion in the studied area – either by tidal currents or by fluvial scouring – was about 60m below present sea-level.

Acknowledgements

A.C. Liu studied from 1986–1990 at the Renard Centre of Marine Geology (RCMG), where he obtained his Ph.D. He gratefully acknowledges research grants from the University of Ghent and from the Science Policy Office, Belgium. He is also grateful to all his colleagues at RCMG for their collaboration (and help) in all stages of the seismic investigations.

RCMG's seismic research in the southern North Sea is supported by the Belgian Science Policy Office, by the Management Unit of the Mathematical Model of the North Sea which made ample ship time available on board of R.V. 'Belgica', by the Ministry of Economic Affairs, including the Administration of Mines and the Belgian Geological Survey, by the National Fund for Scientific Research and by the Ministry of Education of the Flemish Government.

Special gratitude goes to Dr. T.D.J. Cameron for thoroughly reviewing earlier drafts of this manuscript and to two anonymous referees for their constructive comments.

References

- Balson, P.S. & B. D'Olier 1988 Thames Estuary, sheet 51°N-00°E, solid geology. Brit. Geol. Survey & Rijks Geol. Dienst 1:250,000 series
- Balson, P.S. 1989 Neogene deposits of the UK sector of the Southern North Sea (51–53°N). In: J.P. Henriët & G. De Moor (eds.): *The Quaternary and Tertiary geology of the Southern Bight, North Sea*. Belg. Geol. Dienst, Brussel: 89–96
- Bridgland, D.R. & B. D'Olier 1989 A preliminary correlation of the onshore and offshore courses of the River Thames and Medway during the Middle and Upper Pleistocene. In: J.P. Henriët & G. De Moor (eds.): *The Quaternary and Tertiary Geology of the Southern Bight, North Sea*. Belg. Geol. Dienst, Brussel: 161–172
- Cameron, T.D.J., M.S. Stoker & D. Long 1987 The history of the Quaternary sedimentation in the UK sector of the North Sea basin – *J. Geol. Soc. Lond.* 144: 43–58
- De Batist, M. 1989 Seismostratigrafie en structuur van het Paleogeen in de zuidelijke Noordzee. Unpublished doctoral thesis, Universiteit Gent, Belgium. Vol 1: 107 pp., Vol. 2: 136 figs.
- De Moor, G. 1988 The Flemish Valley and the Quaternary river morphology in northern Belgium – *Belg. Ver. Aardr. Studies. – Soc. Belg. Geogr.* 57: 31–85
- Destombes, J.P., E.R. Shepard-Thorn, J.H. Redding & M.T. Morzadec-Kerfourn 1975 A buried valley system in the Strait of Dover – *Phil. Trans. R. Soc. Lond. A.* 279: 243–256
- Donovan, D.T. 1973 The geology and origin of the Silver Pit and other closed basins in the North Sea. *Proc. Yorkshire Geol. Soc.* 39(13): 267–293
- Henriët, J.P., A. Bastin & J. De Rouck 1978 Integration of continuous seismic profiling in geotechnical investigations of the Belgian coast – *Proc. 7th Intern. Harbour Congress, K.V.IV: 1.18/1–1.18/13*
- Henriët, J.P., M. De Batist, H. De Bruyne, Ph. Heldens, J.P. Huylebrouck, F. Mostaert, E. Sevens, J.P. Auffret & B. D'Olier 1989 Preliminary seismic-stratigraphic maps and type sections of the Paleogene deposits in the Southern Bight of the North Sea. In: J.P. Henriët & G. De Moor (eds.): *The Quaternary and Tertiary geology of the Southern Bight, North Sea*. Belg. Geol. Dienst, Brussel: 29–44
- Houbolt, J.J.H.C. 1968 Recent sediments in the Southern Bight of the North Sea – *Geol. Mijnbouw* 47: 245–273
- Joon, B., C. Laban & J.J.M. Van Der Meer 1990 The Saalian glaciation in the Dutch part of the North Sea – *Geol. Mijnbouw* 69: 151–158
- Kellaway, G.A., J.H. Redding, E.R. Shepard-Thorn & J.P. Destombes 1975 The Quaternary history of the English Channel – *Phil. Trans. R. Soc. Lond. A.* 279: 189–219
- Kirby, R. & E. Oele 1975 The geological history of the Sandettie-Fairy Bank area, Southern North Sea – *Phil. Trans. R. Soc. Lond. A.* 279: 257–267
- Laban, C. & R.T.E. Schüttenhelm 1981 Some new evidence on the origin of the Zeeland Ridges – *Spec. Publ. Int. Ass. Sediment.* 5: 239–245
- Liu, A.C. 1990 A seismic and geomorphological study of the erosion surface at the top of the Tertiary in the Southern North Sea (Belgian and northern French sectors). Unpublished doctoral thesis, Universiteit Gent, Belgium. Vol. 1: 119 pp., Vol. 2: 97 figs.
- Liu, A.C., T. Missiaen & J.P. Henriët 1992 The morphology of the Top-Tertiary erosion surface in the Belgian sector of the North Sea – *Mar. Geol.* 105: 275–284
- Maenhaut van Lemberge, V. 1991 Technical report of the Belgian borehole BGS89/1. Commission of the European Communi-

- ties: Directorate General XII, Contract No SCI* 0128-C, Int. Rep.
- Mostaert, F., J.P. Auffret, M. De Batist, J.P. Henriët, A. Moons, E. Sevens, I. Van Den Broecke & M. Verschuren 1989 Quaternary shelf deposits and drainage patterns off the French and Belgian coasts. In: J.P. Henriët & G. De Moor (eds.): *The Quaternary and Tertiary geology of the Southern Bight, North Sea*. Belg. Geol. Dienst, Brussel: 111–118
- Mostaert, F. & G. De Moor 1989 Eemian and Holocene sedimentary sequences on the Belgian coast and their meaning for sea-level reconstruction. In: J.P. Henriët & G. De Moor (eds.): *The Quaternary and Tertiary geology of the Southern Bight, North Sea*. Belg. Geol. Dienst, Brussel: 137–148
- Oele, E. 1971 *The Quaternary geology of the southern area of the Dutch part of the North Sea* – Geol. Mijnbouw 50: 461–474
- Oele, E. & R.T.E. Schüttenhelm 1979 Development of the North Sea after the Saalian glaciation. In: E. Oele, R.T.E. Schüttenhelm & A.J. Wiggers (eds.): *The Quaternary history of the North Sea*. Acta Univ. Upsaliensis Symp. Upsaliensis Annum Quingentesimum Celebrantis 2: 191–216
- Paepe, R., C. Baeteman, R. Mortier, R. Vanhoorne & Centre for Quaternary Stratigraphy 1981 *The marine Pleistocene sediments in the Flanders area* – Geol. Mijnbouw 60: 321–330
- Smith, A.J. 1985 A catastrophic origin for the paleovalley system of the eastern English Channel – Mar. Geol. 64: 65–75
- Sommé, J. 1979 Quaternary coastline in northern France. In: E. Oele, R.T.E. Schüttenhelm & A.J. Wiggers (eds.): *The Quaternary history of the North Sea*. Acta Univ. Upsaliensis Symp. Univ. Upsaliensis Annum Quingentesimum Celebrantis 2: 147–158
- Spaink, G. 1981 Boring RGD 80MK127. Rijks Geol. Dienst, Haarlem, Afd. Macropaleontologie, Int. Rep. 1395
- Spaink, G. & B.C. Sliggers 1979 Boring RGD57. Rijks Geol. Dienst, Afd. Macropaleontologie., Int. Rep. 211
- Thomson, M.E. & R.A. Eden 1977 Quaternary deposits of the central North Sea, 3. *The Quaternary sequence in the west central North Sea*. Rep. Inst. Geol. Sc., London, 77/12
- Wingfield, R.T.R. 1990 *The origin of major incisions within the Pleistocene deposits of the North Sea* – Mar. Geol. 91: 31–52
- Ziegler, P.A. 1981 Evolution of sedimentary basins in North-West Europe. In: L.V. Illing & G.D. Hobson (eds.): *Petroleum geology of the continental shelf of North-West Europe*. Institute of Petroleum, London: 3–43