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Met vriendelijke groeten,
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Seismic sequence stratigraphy of the Palaeogene offshore of Belgium, southern North Sea

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Abstract: A fine-scale seismic stratigraphic model has been developed for the Palaeogene of the southern North Sea on the basis of interpretation of a dense high-resolution reflection seismic grid, covering the Belgian sector of the continental shelf and the adjacent parts of the Dutch, French and UK sectors. Classical seismic stratigraphic criteria have allowed up to 13 major units to be defined; the geometry and seismic facies characteristics of each have been analysed in detail. The seismic stratigraphy has been compared with the results of four offshore boreholes. 'Events and trends' identified on seismic sections and in outcrops in northern Belgium have been correlated, and offshore seismic facies have been tentatively matched with onshore lithofacies. The geological history of the study area is discussed in terms of eustatic sea level changes and regional tectonic events, and the main characteristics of the offshore Palaeogene deposits are evaluated in a sequence stratigraphic context.

Keywords: North Sea, sequence stratigraphy, Palaeogene, seismic profiles, shelf environment.

The area in the southern North Sea between 51°-52° N and 2°-3.5° E encompasses the Belgian sector of the continental shelf and adjacent parts of the Dutch, French and UK sectors (Fig. 1). It constitutes the offshore part of the so-called 'Belgian Basin', that forms a bight-like extension of the southern North Sea Basin. It can be regarded as the eastern counterpart of the London Basin.

This Belgian Basin is entirely situated on top of the London-Brabant Massif, a relatively stable continental block of Palaeozoic age, that was not flooded until Late Cretaceous times. The Cenozoic stratigraphic record, well known from numerous outcrops in northern Belgium (Marechal & Laga 1988; Vandenberghe *et al*. 1995), is almost completely marine to marginal marine. A shallow shelf environment persisted through the Palaeogene and the area was periodically flooded during periods of high relative sea level. Water depths probably never exceeded 100 m, and were usually far less (Cameron *et al*. 1992). The Neogene was a period of sediment starvation as the depocentre shifted north of the area into the main North Sea Basin. In Quaternary times, the area emerged repetitively in response to glacio-eustatic sea level falls. The Holocene flooded shelf has remained essentially sediment starved.

In the Belgian Basin, the Palaeogene strata on top of the Late Cretaceous chalk are gently dipping (0.5–1°) to the northeast. The Palaeogene strata in the offshore area crop out locally on the sea bed, between a discontinuous cover of Quaternary sediments (e.g. the Flemish Banks).

A first attempt to investigate the geology offshore Belgium in detail was undertaken by Bastin (1974). The present study, of which some preliminary results have already been presented by Henriet *et al*. (1989*a, b*) and De Batist *et al*. (1989), represents the first comprehensive investigation of the stratigraphy and structural setting of the Belgian continental shelf. It is complementary to the palaeomorphologic studies of Mostaert *et al*. (1989) and Liu *et al*. (1992, 1993), and to the lithostratigraphic investigations of Jacobs *et al*. (1991) and Jacobs & Sevens (1993).

Available seismic database

Since 1978, the Renard Centre of Marine Geology (RCMG) has been carrying out high-resolution reflection seismic investigations in the southern North Sea. The resulting seismic grid currently reaches a total length of about 16 000 km (Fig. 2). Profiles have been shot with different seismic tools, allowing information to be gathered on the architecture of the full Mesozoic–Cenozoic section and this with an optimal resolution. Seismic processing of the multi-channel digital data has also yielded some relevant seismic velocity information.

In sharp contrast with this extensive seismic data base, there is only limited borehole information. Only four shallow cored boreholes have been drilled offshore of Belgium, through the Quaternary drift into the Tertiary substratum (Fig. 2). Grain size, facies and sequence analyses were performed on these cores by Jacobs *et al*. (1991) and Jacobs & Sevens (1993) (Fig. 3). Unfortunately, integration of these data with the seismic information has not been straightforward as most of the boreholes were located in shallow water areas, characterized on the seismic profiles by acoustic blanking due to superficial gas. Only borehole VR1 can be tied directly to the seismic data.

Seismic stratigraphic approach

The detailed interpretation of the available seismic data set, following the basic principles defined by Mitchum *et al*. (1977), has allowed 13 stratigraphic units and a number of sub-units to be identified. Unit boundaries are surfaces of consistent reflector termination. Downlap is frequently observed on the basal surfaces, whereas coastal onlap occurs only sporadically. Erosional truncation and valley incisions are common features at the top of the units, but the seismic data do not always provide sufficient evidence to identify all of them as unconformities *sensu stricto* (Van Wagoner *et al*. 1988), i.e. surfaces of subaerial exposure and erosion and their correlative submarine surfaces of erosion.

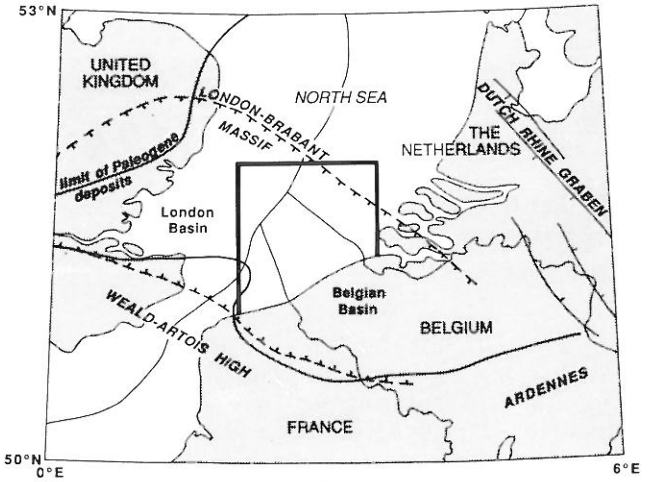

Fig. 1. Location of the study area.

Each unit is also characterized by a distinct seismic facies and/or by typical facies variations, bearing witness to the sedimentary environment and to the depositional and diagenetic history.

The units have been assigned a character-digit symbol, indicating their most probable chronostratigraphic position. The identified units are:

T1 and T2 (Thanetian);
Y1, Y2, Y3, Y4 and Y5 (Ypresian):
L1 and L2 (Lutetian);
B1 (Bartonian);
P1 (Priabonian);
R1 and R2 (Rupelian).

The subcrop pattern of these units at the base of the Quaternary cover, where present, is shown on Fig. 4, and their seismic stratigraphic characteristics have been compiled into a schematic type section (Fig. 5) and a synthesis (Table 1).

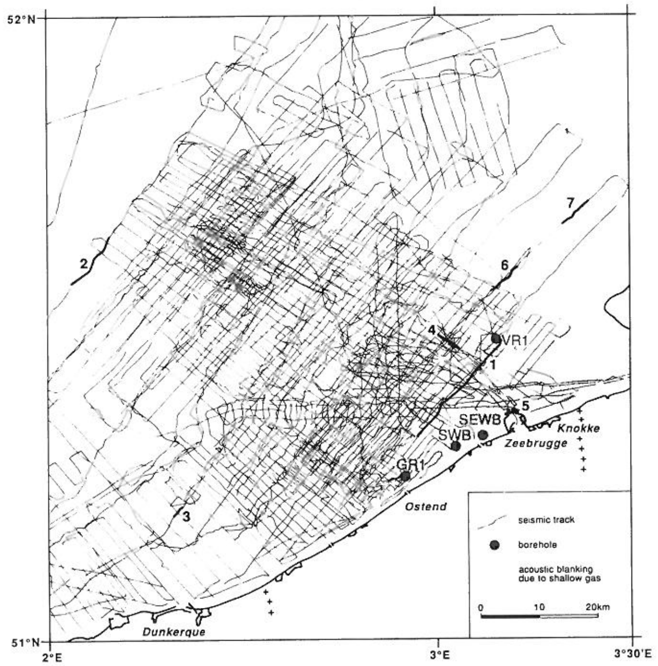

Fig. 2. Map showing the available seismic grid and the locations of the boreholes referred to in the text. Location of seismic profiles: 1, Fig. 3; 2, Fig. 8; 3, Fig. 9; 4, Fig. 10; 5, Fig. 11; 6, Fig. 12; 7, Fig. 13.

Correlation criteria

The seismic stratigraphy defines the geometrical arrangement of the strata on the continental shelf fairly well. Part of the Palaeogene section can also be tied to the VR1 borehole (Fig. 6), which is correlated by Jacobs & Sevens (1993) with the onshore deposits of Belgium. However, the lack of other direct lithological or palaeontological data makes it difficult to fit the rest of the offshore succession into a reliable chrono- or lithostratigraphic framework. Nevertheless, a number of arguments and observations are at hand for an indirect correlation: e.g. the geometrical fit of sediment bodies across the onshore–offshore boundary, the identification of the major transgressive–regressive cycles, the correlation of tectonically enhanced unconformities in the onshore and offshore areas, the comparison of lithofacies and seismic facies, the analysis of the morphological expression of seismic stratigraphic units outcropping at the erosion surface at the base of the Quaternary in the offshore domain, etc.

Geometrical fit of onshore and offshore units

A first and very straightforward correlation procedure involved the simple geometrical fit of surfaces and units on either side of the data gap formed by the nearshore zone, taking into account strike and dip of the surfaces, thickness variations of the units, outcrop patterns, etc.

Correlation of onshore and offshore 'events and trends'

Another approach involved the identification and correlation of 'events and trends' within the stratigraphic section onshore and offshore, such as transgressive-regressive cycles, major erosive events and tectonically enhanced unconformities (Fig. 7).

Vail *et al.* (1991) propose that transgressive-regressive cycles on a continental margin are the result of second order relative sea level changes. They are convolved with the third and higher-order eustatic signal, producing a complex curve with global (eustatic) as well as regional (subsidence, sediment supply) influences. During peak second order transgressions, wide and stable continental shelves (e.g. the Belgian Basin during the Palaeogene) will remain flooded for most of the time and will be subject to a nearly continuous sedimentation. Depending on the position on the shelf and on the amount and type of the supplied sediment, relatively thick packages of homogeneous clayey sediments may be deposited, representing the stacked distal parts of several third order sequences. During peak second order regressions, the continental shelf will become increasingly emerged and third order eustatic lowstands will result in widespread erosion. In this case, the stratigraphic record will be discontinuous and incomplete.

It has been recognized for more than a century that a number of such major transgressive–regressive cycles exist in the Palaeogene of the Belgian Basin (e.g. Rutot 1883;

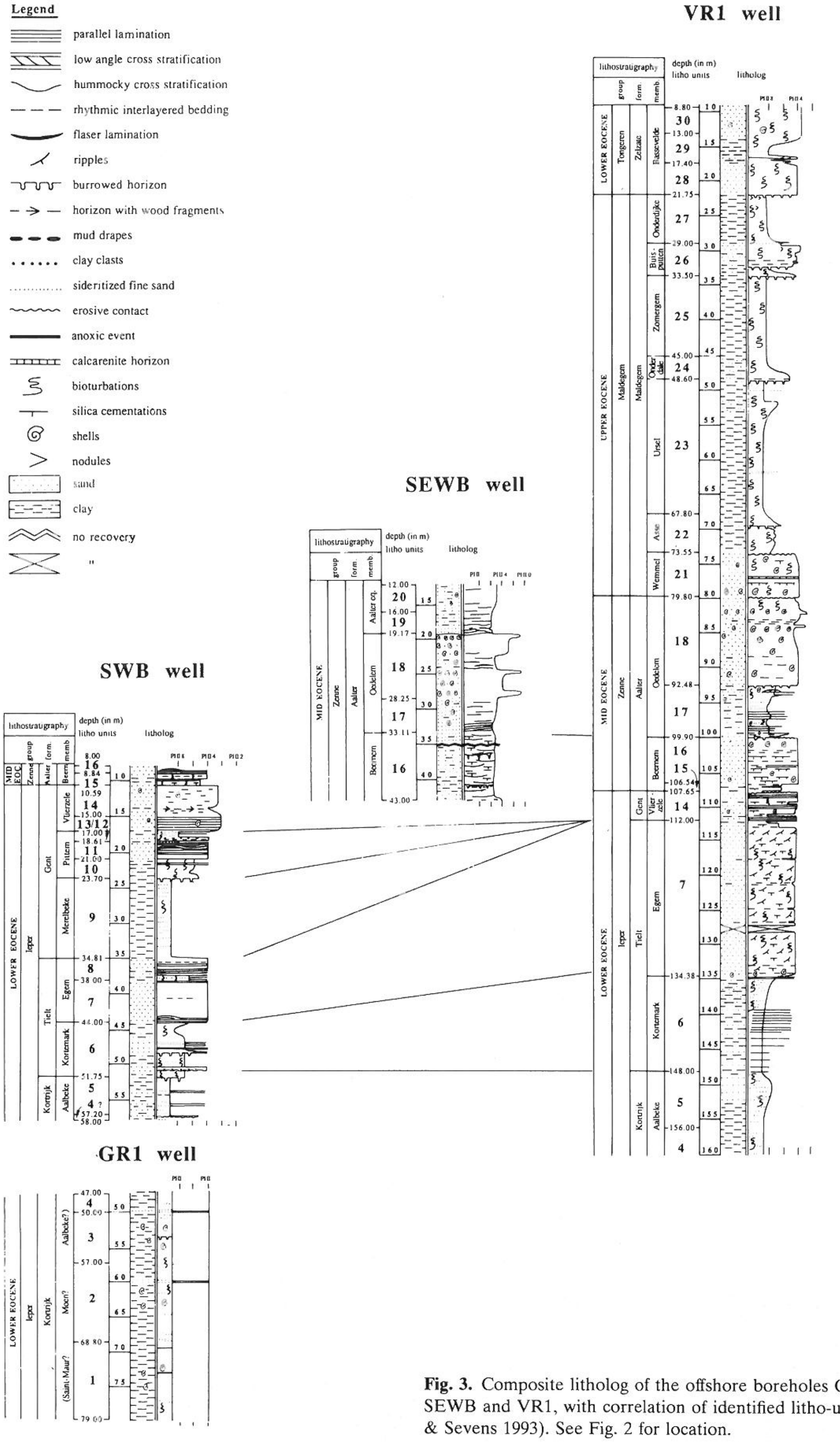

Fig. 3. Composite litholog of the offshore boreholes GR1, SWB, SEWB and VR1, with correlation of identified litho-units (from Jacobs & Sevens 1993). See Fig. 2 for location.

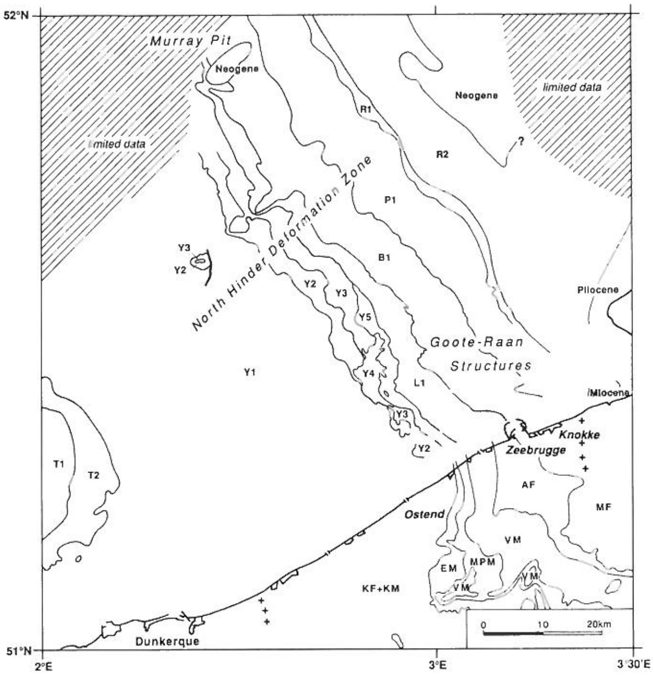

Fig. 4. Simplified map showing the subcrop pattern of the Palaeogene seismic stratigraphic units (offshore) and lithostratigraphic units (onshore) beneath the Quaternary cover, and the location of the main structures. KF, Kortrijk Formation; KM, Kortemark Member; EM, Egem Member; MPM, Merelbeke and Pittem Members; VM, Vlierzele Member; AF, Aalter Formation; MF, Maldegem Formation.

Gullentops *et al.* 1988). Each peak second order transgression corresponds with a well-developed clay deposit. These deposits include:

(i) the Kortrijk Formation or 'Ieper clay' of early Ypresian age (Steurbaut & Nolf 1986),
(ii) the Maldegem Formation or 'Kallo Complex' of Lutetian to Bartonian age (Jacobs 1978),
(iii) the Boom Formation or 'Boom clay' of Rupelian age (Vandenberghe 1978).

Seismic stratigraphic criteria (Table 1; Fig. 7) have allowed these peak second order transgressions to be also identified offshore, where they are represented by the relatively thick Y1, B1 and R2 units, associated with seismic facies that suggest a quasi-continuous and homogeneous deposition.

Erosional truncation and valley incision or subaerial exposure indicate third order relative sea level falls, the effects of which are enhanced during peak second order regressions. A number of major incisions have been reported from the onshore Belgian Palaeogene:

(i) at the base of the (Thanetian) continental/lagoonal Tienen Formation (Leriche 1928; Demyttenaere 1989; De Batist & Versteeg 1993),
(ii) at the base of the (Late Ypresian) Vlierzele Member (Steurbaut & Nolf 1986),
(iii) at the top of the (Rupelian) Boom Formation (Vinken 1988; De Batist & Versteeg 1993).

Offshore, it is also possible to identify a number of incised valleys (Table 1; Fig. 7). They occur at the base of and within unit T2, at the base of unit Y4, and at the top of unit R2.

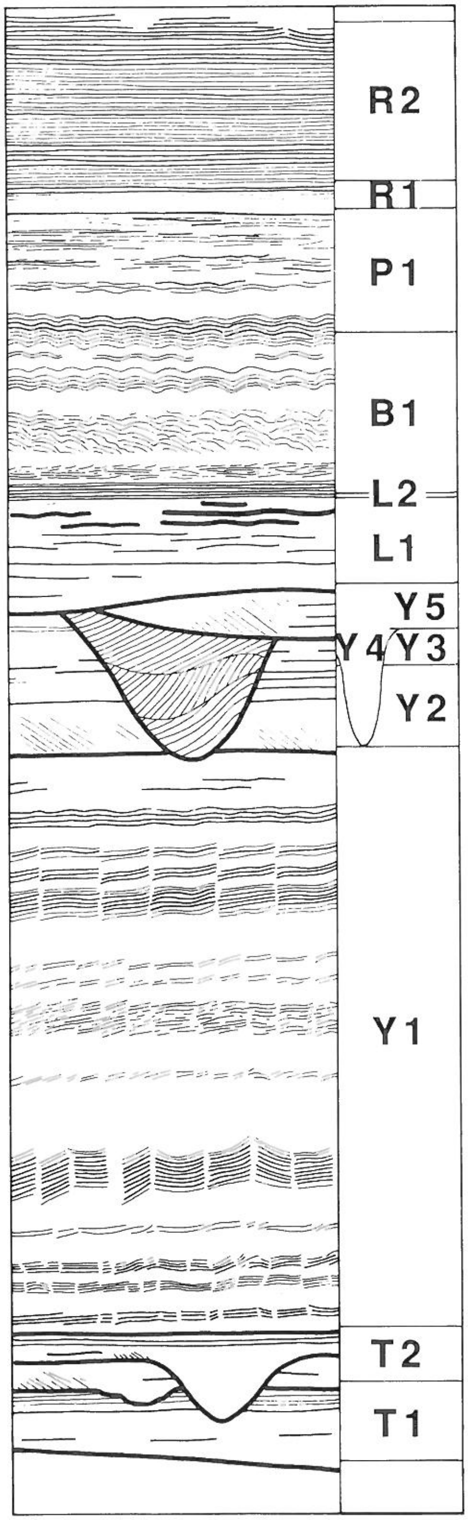

Fig. 5. Schematic seismic stratigraphic type section for the offshore Belgian Basin.

Tectonic events in the offshore domain are documented by synclinal folds and faults (Henriet *et al.* 1989b), which are associated with structural truncation at tectonically enhanced unconformities (Fig. 7). These occur at the base of units T1, L2 and R1. Onshore, such tectonic events have not

Table 1. *Seismic stratigraphic characteristics of the 13 units in the offshore Belgian Basin*

Unit	Nature of base	Nature of top	Seismic facies	Geometry
R2	Conformity	Erosional truncation channel incision	Regular pattern of continuous, parallel, high- to medium-amplitude reflectors	Planar dipping base; strongly incised & channelized top Thickness: 0–60 m ($v = 1650$ m s^{-1})
R1	Discrete downlap	Discrete truncation	Discontinuous, subparallel to wavy reflectors with variable amplitude	Planar dipping base; planar dipping top Thickness: ±35 m ($v = 1700$ m s^{-1})
P1	Discrete onlap	Discrete truncation	Vertical succession of two seismic facies units: (2) homogeneous pattern of continuous, parallel, low- to medium-amplitude reflectors (1) continuous, parallel, draping reflectors of variable amplitude	Planar dipping base; planar dipping top; divergent to NE Thickness: 40–90 m ($v = 1700$ m s^{-1})
B1	Conformity	Conformity	Vertical succession of seven seismic facies units: (7) reflection-free with a low-amplitude, discontinuous, draping reflector (6) medium-amplitude, draping reflectors (5) reflection-free (4) convex mounds of medium-amplitude, prograding, hummocky reflectors (3) reflection-free (2) subparallel reflectors with shingled reflector on top (1) regular set of continuous, parallel, high-frequent reflectors	Planar dipping base; Planar dipping top; Thickening to N and NE Thickness: 45–60 m ($v = 1580$ m s^{-1})
L2	?	?	?	Local distribution, very thin
L1	Conformity	Tectonically influenced truncation	Vertical succession of two seismic facies units (2) discontinuous, parallel to subparallel reflectors of variable amplitude; towards the top 2 to 3 discontinuous, subparallel, very high-amplitude reflectors (1) 2 continuous, high-amplitude parallel reflectors, in the S and 3rd discontinuous, low-amplitude reflector	Planar dipping base; Planar dipping top Thickness: 25–30 m ($v = 1700$ m s^{-1})
Y5	Downlap	Truncation and toplap	Three seismic facies units of local areal extent (3) low-amplitude, parallel reflelctors (2) parallel-oblique clinoforms (1) reflection-free	Planar dipping base; planar dipping top; Wedge shape, pinching out towards N Thickness: 0–17 m ($v = 1700$ m s^{-1})
Y4	Downlap	Truncation	Three SE prograding subunits with sigmoidal to parallel–oblique clinoforms of variable amplitude	Linear channelized base; planar dipping top; channel-fill shape (10 km wide, N70E orientation) Thickness: 0–25 m ($v = 1700$ m s^{-1})
Y3	Discrete downlap	Truncation	Low-amplitude, discontinuous, parallel reflectors or parallel-oblique clinoforms	Planar dipping base; planar dipping top, locally channelized Thickness: 0–25 m ($v = 1600$ m s^{-1})
Y2	Downlap	Truncation	Reflection-free or very low-amplitude, parallel-oblique, prograding clinoforms	Planar dipping base; planar dipping top Thickness: ±30 m ($v = 1750$ m s^{-1})
Y1	Conformity	Discrete truncation	Low-amplitude, discontinuous, parallel reflectors, affected by intraformational deformations: top part: undisplaced, faulted blocks with alternately tilting and downwarping bedding terminations central part: major tilted blocks, convolute structures with broad synclines and cusp anticlines, diapirs lower part: block-faulting, tilted and bent blocks, randomly dipping fault planes	Planar dipping base; planar dipping top; thickening to NE Thickness: 150–180 m ($v = 1620$ m s^{-1})
T2	Downlap	Truncation	Oblique or shingled clinoforms and low-amplitude, discontinuous, supparallel or hummocky reflectors; incised channels at base and at some metres above base	Planar dipping base, locally channelized; planar dipping top Thickness: 15–20 m ($v = 1800$ m s^{-1})
T1	Onlap	Truncation	Few parallel reflectors of variable amplitude, separated by reflection-free intervals	Irregular base (erosional surface); planar dipping top Thickness: 15–30 m ($v = 1800$ ms^{-1})

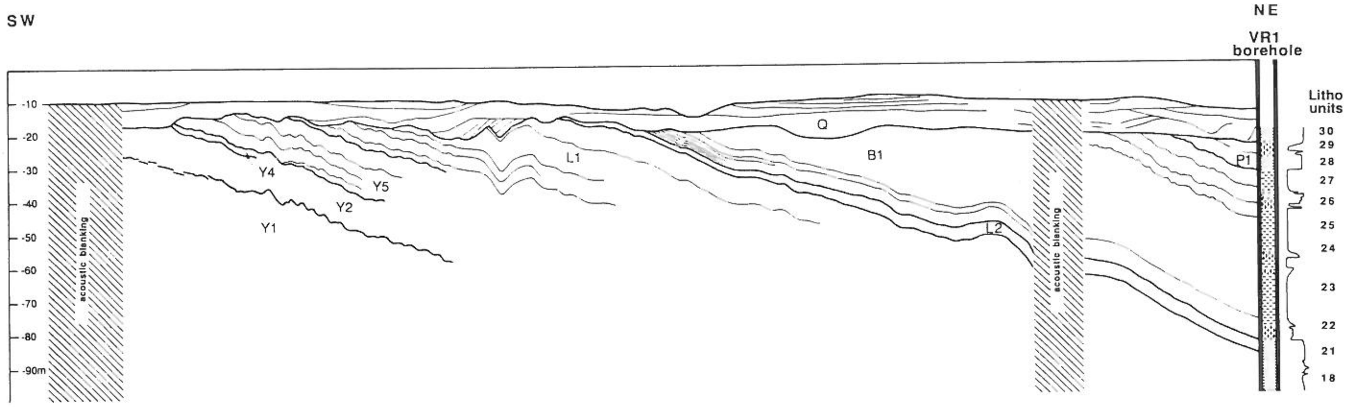

Fig. 6. Interpreted line-drawing of sparker section through borehole VR1. Correlation of seismic stratigraphic units and litho-units of Jacobs & Sevens (1993).

been identified, but a number of distinct angular unconformities are known and have been assigned to differential movements of the London–Brabant Massif (Demyttenaere 1989; Vandenberghe *et al.* 1995). These unconformities occur at:

(i) the base of the (Thanetian) Hannut Formation (Vandenberghe *et al.* 1995),

(ii) the base of the (Lutetian) Lede Formation (Vandenberghe *et al.* 1995),

(iii) the Eocene-Oligocene boundary, at the base of the (Rupelian) Niel Formation (Steurbaut 1992; Demyttenaere & Laga 1988; De Batist & Versteeg 1993).

On Fig. 7, a clear relationship can be observed between these three tectonic pulses and some of the peak second order regressions, arguing for a significant regional tectonic overprint on eustasy.

Comparison of onshore lithofacies and offshore seismic facies

In order to assess the lithology of the seismic units, their seismic facies and their morphological expression at outcrops and subcrops were analysed. Such an exercise is of specific interest, as within the Belgian Basin most of the stratigraphic units are characterized by rapid, wholescale lateral facies changes, inherent to the marginal position of the area within the North Sea Basin.

Palaeocene

Thanetian Units T1 and T2

The Cenozoic history of the area starts with the deposition of unit T1, of Thanetian age and correlated with the Hannut Formation of NW Belgium and the Thanet Formation of SE England. Its seismic facies (Table 1) is consistent with the low-energy shallow-marine environment, described by De Geyter (1981) for the Hannut Formation.

Unit T1 is separated from the Late Cretaceous chalk by a pronounced regional onlap surface. Seismic profiles show this erosional surface to be smooth and nearly parallel to the reflectors in the underlying chalk in most of the study area. However, in the extreme west of the area, in the prolongation of a major SW–NE-trending structural lineament (the North Hinder Deformation Zone; Henriet *et al.* 1989*b*; Fig. 4) Thanetian palaeo-highs correspond with anticlinal structures (Fig. 8), trending N70°E to N95°E. The top chalk erosion surface is therefore most likely structurally controlled (Fig. 7). This suggests a weak Late Cretaceous to Mid-Palaeocene tectonic pulse, which is consistent with the Mid- to Late Palaeocene tectonic phase identified by Knox (1989) in adjacent areas offshore. Also Vandenberghe *et al.* (1995) invoke tectonics to explain the highly variable facies and distribution of Palaeocene deposits in N Belgium.

T1's lower boundary can be regarded as a tectonically enhanced unconformity and unit T1 possibly represents a depositional sequence, composed of a transgressive systems tract at its base (the basal onlapping part) and a highstand systems tract at the top.

The overlying unit T2 can be correlated with the continental to lagoonal Tienen Formation (Knokke Member) of NW Belgium and the marine to lagoonal Woolwhich/Reading Beds plus the Oldhaven Member of SE England. Distinct channel cut-and-fill structures can be observed on the seismic sections at the base and at some metres above the base of unit T2 (Fig. 9), defining two erosional surfaces. The incisions are most likely related to Thanetian eustatic sea level falls, but a tectonic influence, related to a first phase of updoming of the Weald–Artois area, cannot be ruled out. The basal channels, up to 20 m deep, seem to be part of a fluvial drainage system, that is oriented towards the east and north-east.

Unit T2 probably contains two sequences, each represented by backfilling channel deposits (late lowstand or transgressive systems tract) and overlying parallel reflections (highstand systems tract). The seismic facies of unit T2 (Fig. 4) could be interpreted as resulting from tidally influenced sedimentation.

Eocene

Ypresian Units Y1 to Y5

During most of the Thanetian and Ypresian Stages the study area was part of a shallow sea that extended westwards into the English channel. The rising Weald–Artois High started to form a barrier closing the connection to the English Channel from Lutetian times onwards (Cameron *et al.* 1992), and possibly even earlier (Dupuis *et al.* 1984).

Five seismic units, Y1 to Y5, have been designated an Ypresian age. They have already been described in some

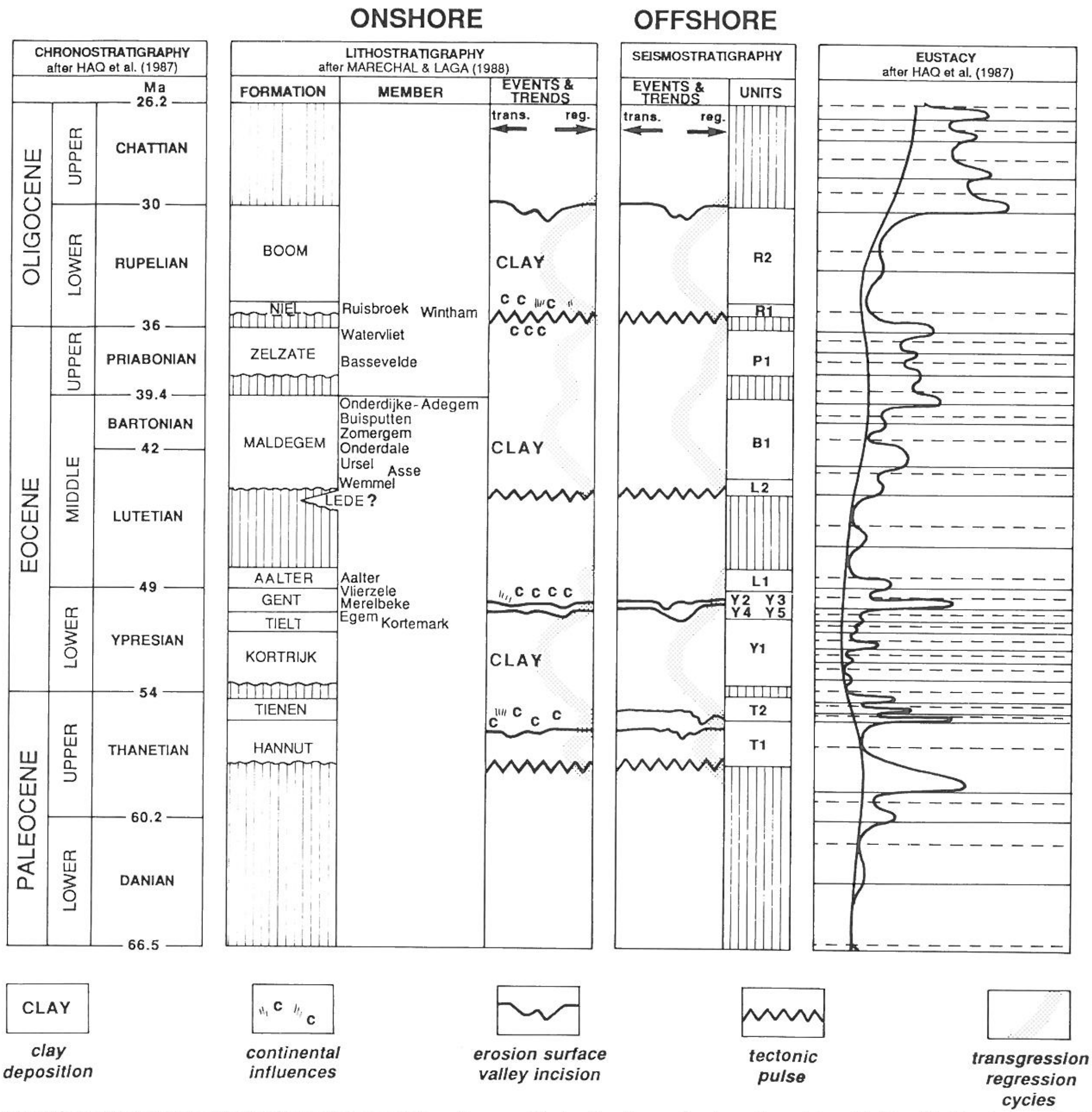

Fig. 7. Synoptic seismo-chrono-lithostratigraphic correlation diagram illustrating the major 'events and trends' identified both in and offshore of Belgium.

detail by De Batist *et al.* (1989) and Henriet *et al.* (1988, 1991) and elsewhere.

Unit Y1 reaches a thickness of more than 150 m, and its subcrop covers a large part of the area (Fig. 4). It correlates with the 'Ieper clay' of Belgium, which includes the Kortrijk Formation and the Kortemark Member of the Tielt Formation, and its equivalent in southern England, the London Clay Formation. A seismic marker about 4 m above the conformable base of unit Y1 can be correlated with the Harwich Stone Band in the Thames Estuary. The latter represents a volcanic ash layer, deposited during the intense volcanism associated with the onset of sea floor spreading north of Scotland (Knox & Morton 1988). Unit Y1 is characterized by a homogeneous seismic facies, suggesting a relatively long period of stable, low-energy depositional environments. Onshore, the 'Ieper clay', interpreted to be deposited in a mud-shelf environment (Jacobs & Sevens 1993), is subdivided into five members (Marechal & Laga 1988) and into five depositional sequences (Vandenberghe *et al.* 1995). These cannot be identified on the seismic sections, because the internal reflection pattern is strongly disturbed by a wide range of intraformational 'sediment tectonic' deformations (Table 1; Fig. 9), which have been described by Henriet *et al.* (1982, 1988), De Batist *et al.* (1989) and Cameron *et al.* (1992). These deformations, some of which have also been observed and structurally analysed onshore, have been related by Henriet *et al.* (1991) to the relaxation of temporary states of density inversion linked to undercompaction in the early burial history of the clayey–silty sediment.

The overlying units Y2 and Y3 are correlated respectively with the Egem Member of the Tielt Formation

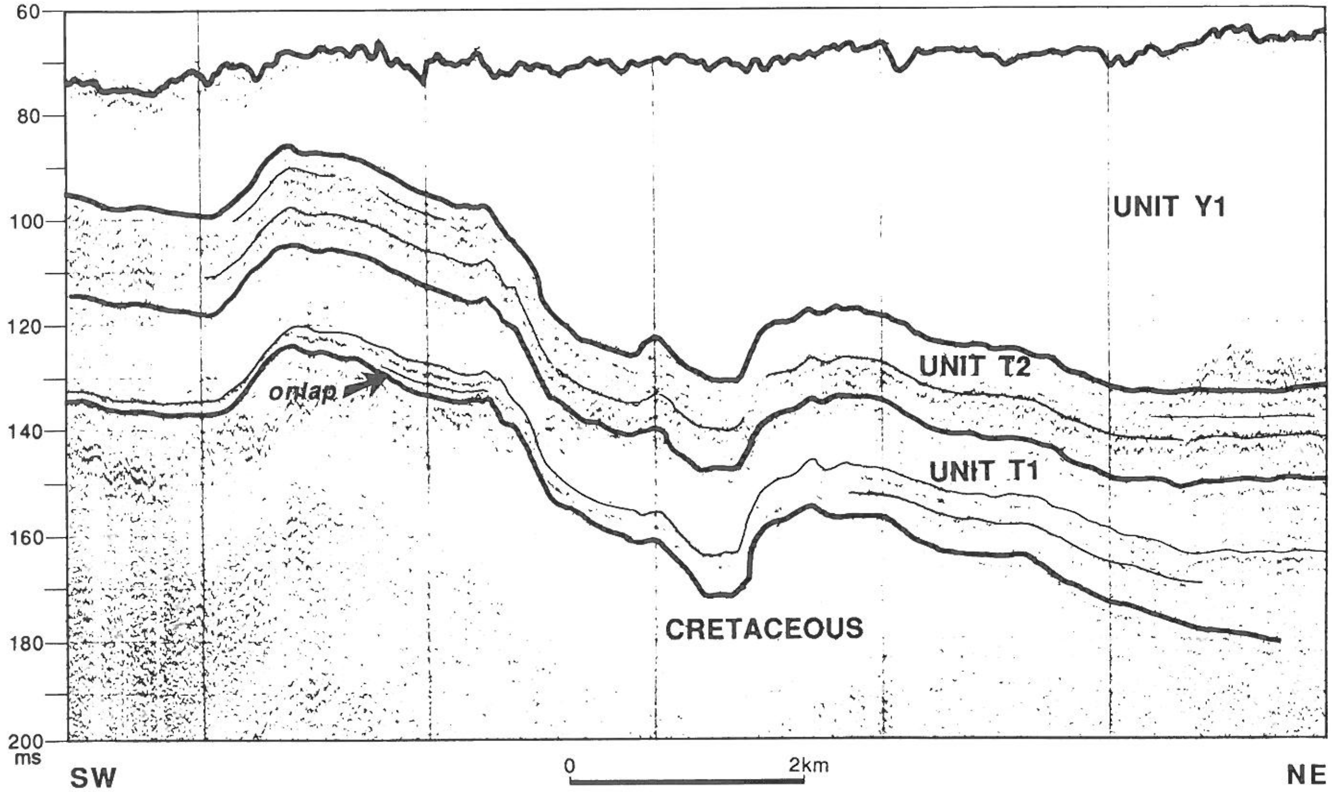

Fig. 8. Interpreted sparker section showing characteristic basal onlap of unit T1 against the structurally controlled palaeomorphology at the top of the Chalk. See Fig. 2 for location.

and the Merelbeke and Pittem Members of the Gent Formation in the Belgium nearshore area, which consist of deltaic sands and offshore mud-flat and sand-shoal deposits respectively (Jacobs & Sevens 1993). They are both characterized by distinct lateral seismic facies variations, and towards the basin centre they become undistinguishable from the underlying unit Y1. The boundary between Y1 and Y2 is a laterally continuous, very high-amplitude reflection, one of the best seismic markers in the whole of the Palaeogene section in the study area. It is interpreted as a sequence boundary, overlain by downlapping lowstand deposits. This is in agreement with the sequence stratigraphic interpretation of the Egem Member by Vandenberghe *et al.* (1995).

Unit Y4 is confined to a channel or basin, trending N70°E, some 20 km N of Ostend. The channel is locally more than 10 km wide and is deeply (20–25 m) incised in the underlying strata. Unit Y4 displays 3 infilling stages, with progradation from NW to SE (De Batist *et al.* 1989). The infilling sediments form a local high in the erosion morphology at the base of the Quaternary deposits (Liu *et al.* 1992). Separated from unit Y4 by an erosion surface, unit Y5 is restricted to the southern part of the area. It extends however beyond the incised channel or basin. A number of different facies sub-units can be identified within the unit. Some consist of parallel reflections; others of eastward prograding reflections.

Units Y4 and Y5, both deposited following strongly erosive events, most likely correlate with the cross-bedded sands of the Vlierzele Member (Gent Formation) in Belgium. The latter has been interpreted as a tidal ridge system (Houthuys & Gullentops 1988), which is not inconsistent with the observed seismic facies. Vandenberghe *et al.* (1995) reported strong erosion at the base of the Vlierzele Member onshore (Fig. 7), and this is also confirmed by the offshore borehole data (Jacobs & Sevens 1993). The erosion surface at the base of unit Y4 is therefore clearly a sequence boundary, while the channel infill and the overlying unit Y5 could represent respectively the lowstand and the transgressive (parallel facies) to highstand (prograding facies) deposits, separated by a ravinement surface. Conversely, the erosion surface at the base of unit Y5 could also be interpreted as a separate sequence boundary. In any case, the seismic data seem to suggest that the offshore Vlierzele Member is composed of more than just a lowstand deposit, as proposed by Vandenberghe *et al.* (1995).

Lutetian Units L1 and L2

The Lutetian unit L1 is the offshore equivalent of the Aalter Formation of Belgium, consisting of a variety of very shallow deposits (tidal flats, lagoons, etc.) as shown by Jacobs *et al.* (1991) and Jacobs & Sevens (1993). Its seismic facies (Table 1) is in agreement with this type of deposits. A number of strong reflections at the top of L1 (Fig. 10) correlate with the calcareous sandstone beds, that were identified near Zeebrugge by Depret (1983). They are indicative of the upward shallowing of the Aalter Formation, the upper part of which has been interpreted by Vandenberghe *et al.* (1995) as a highstand systems tract.

Off Zeebrugge, the strata are offset by normal faults (general strike: N60°E) and deformed by asymmetrical folds

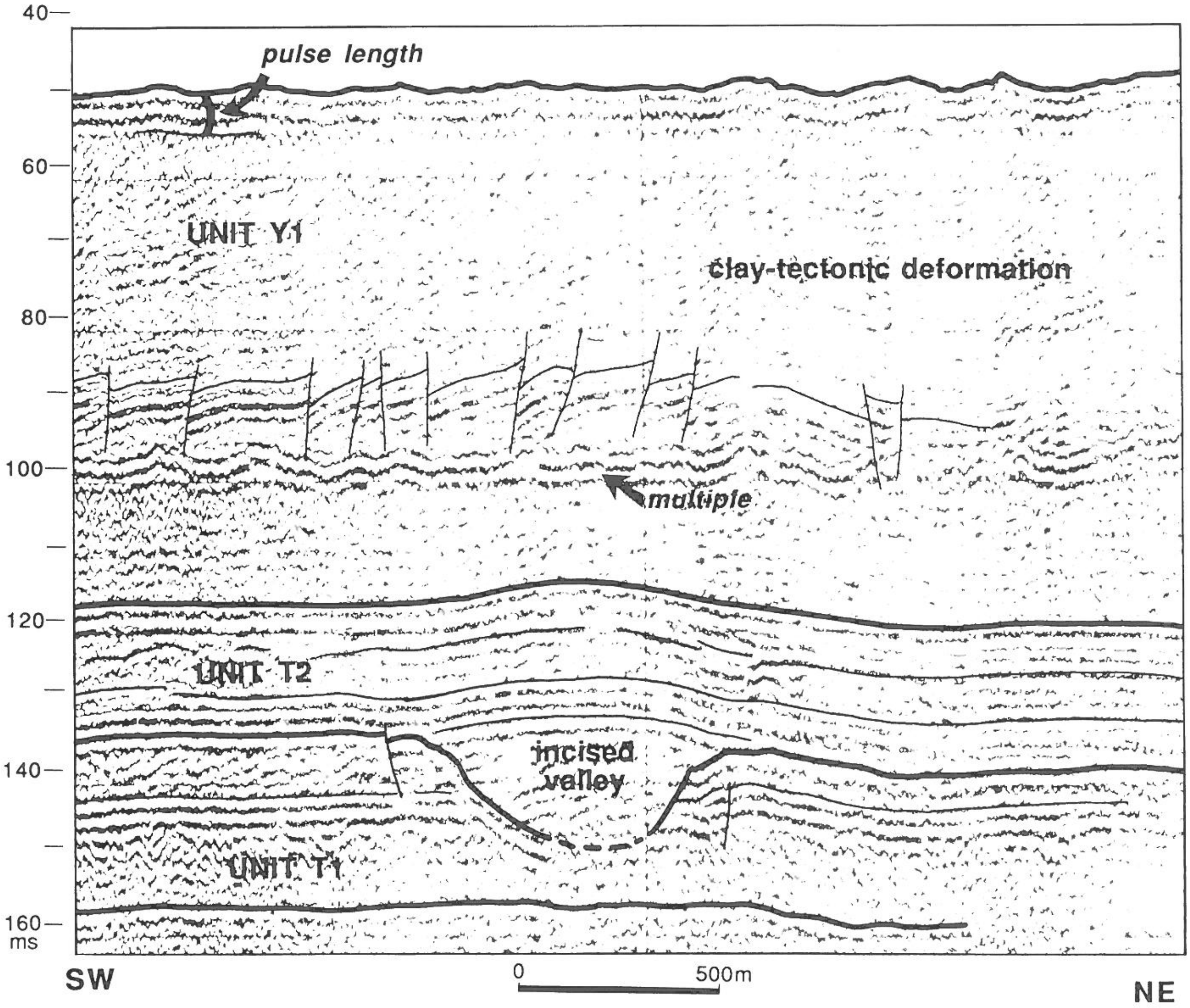

Fig. 9. Interpreted sparker section showing the channel cut-and-fill structures at the base of unit T2 and its typical seismic facies. Differential compaction of the channel fill deposits can be clearly observed. The overlying unit Y1 is affected by intraformational 'sediment tectonic' deformation. See Fig. 2 for location.

(fold axes: N90°E to N100°E): the so-called 'Goote-Raan Structures'. In such areas, the characteristic strong reflectors of L1 are truncated at the crests of the folds. As the main folding phase clearly took place after the Bartonian, the observed truncation pattern indicates an initial deformation phase shortly before deposition of L2. The upper boundary of unit L1 therefore represents a tectonically enhanced unconformity (Fig. 7). This unconformity coincides with a considerable hiatus in the coastal area, where the Brussel and Lede Formations are absent. Vandenberghe *et al.* (1995) relate this to tectonics associated with the Weald–Artois uplift.

Overlying this unconformity, unit L2 is a very thin and locally distributed deposit (Fig. 10). It could represent a lateral equivalent of the uppermost Aalter Formation or of the Lede Formation (Depret & Willems 1983), but it more likely correlates with part of the Wemmel sands of the Maldegem Formation, as is suggested by the interpretaton of the VR1 borehole (Jacobs & Sevens 1993). As such, it would mark the start of a new sedimentation cycle. Determination of L2's exact nature and stratigraphic position remains however difficult due to the limited thickness and areal distribution of the preserved deposits. The characteristics of unit L2 suggest that it may represent a transgressive lag deposit, overlying a ravinement surface that coincides with the sequence boundary.

*Bartonian Unit B*1

Unit B1 has been extensively studied by a dense grid of piston cores in its outcrop area in the course of Zeebrugge's outer harbour expansion project. It reaches a total thickness of about 60 m. In borehole VR1 it correlates with the Maldegem Formation or 'Kallo complex' of northern Belgium (Jacobs & Sevens 1993), which is mainly of Bartonian age. On the seismic profiles, unit B1 is characterized by a very distinctive and laterally continuous succession of seven seismic facies units (Table 1; Fig. 11). These seem to correspond to the 7 lithofacies units of the

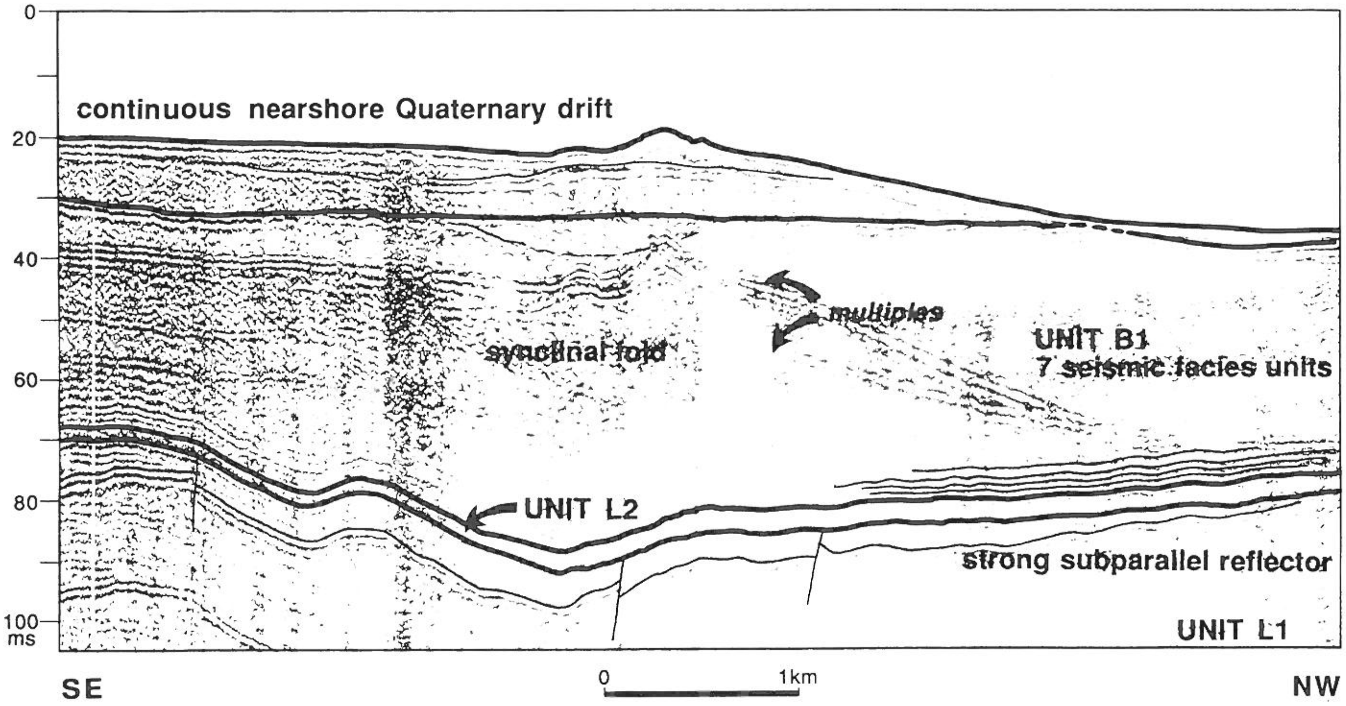

Fig. 10. Interpreted sparker section showing the tectonically enhanced unconformity at the top of unit L1 and the overlying thin unit L2. See Fig. 2 for location.

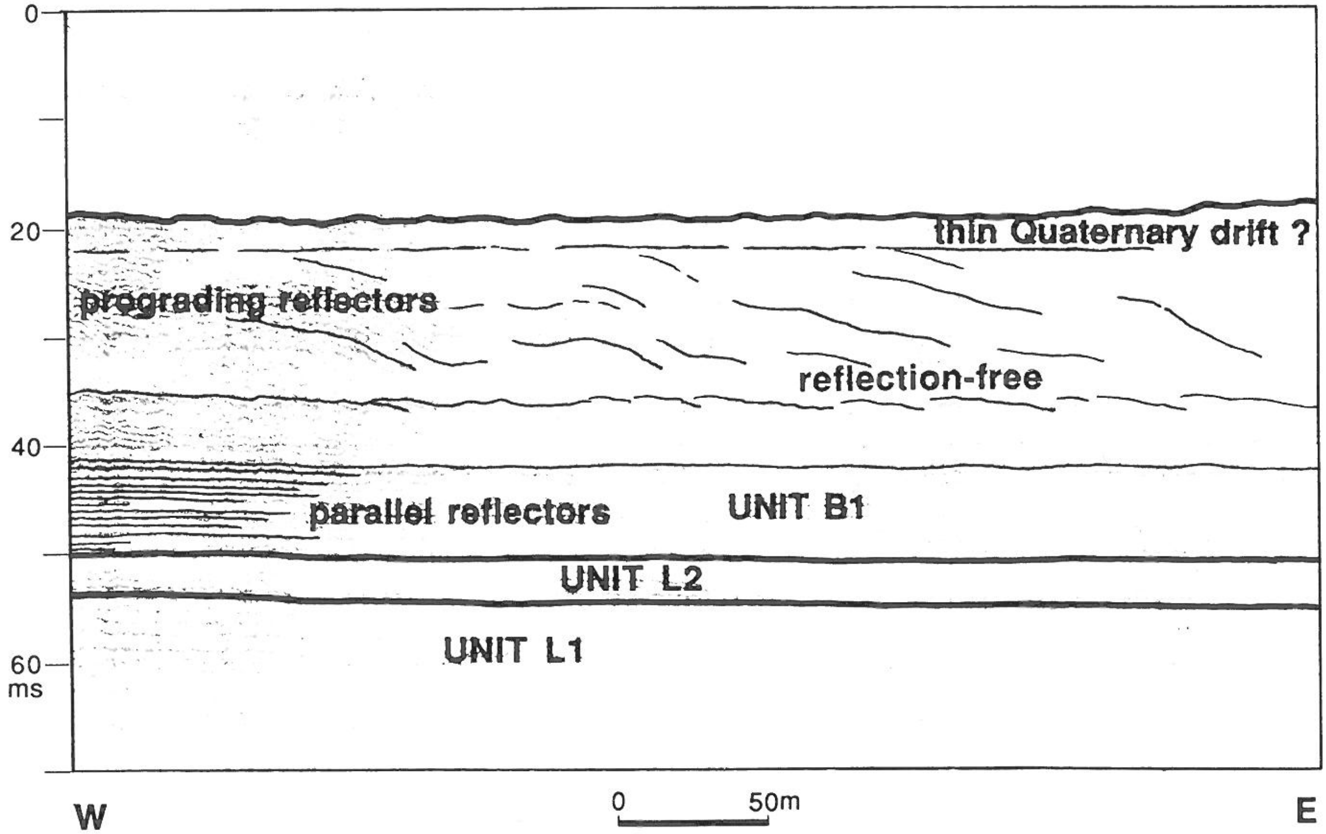

Fig. 11. Interpreted boomer section showing four of the seven seismic facies units of unit B1 (Table 1). The mounds of dipping, hummocky reflectors observed just below the thin Quaternary cover, can be interpreted as prograding clinoforms or as a mobile zone with closely spaced normal, listric faulting. Both are consistent with the deltaic setting proposed by Jacobs & Sevens (1993). See Fig. 2 for location.

Maldegem Formation (Jacobs 1978), characterized by alternations of clays and sands deposited in a distal deltaic setting (Jacobs & Sevens 1993). On basis of grain-size and well-log signatures, Vandenberghe *et al.* (1995) subdivide the Maldegem Formation into three depositional sequences, each composed of transgressive and highstand deposits. Following this interpretation, the observed downlapping seismic facies units of B1 probably represent the highstand systems tracts.

*Priabonian Unit P*1

Unit P1, of Priabonian age, thickens considerably in a basinward direction and correlates with the Zelzate Formation of Belgium, consisting of shallow marine, lagoonal and tidal flat deposits (Steurbaut 1986; Jacobs & Sevens 1993). Its seismic facies (Table 1, Fig. 12) is consistent with this type of environment. The base of this unit is a low-angle coastal onlap surface and therefore a sequence boundary. This is in agreement with the interpretation of Vandenberghe *et al.* (1995), who identified a major sequence boundary at the base of the Zelzate Formation onshore.

In the NE-prolongation of the North Hinder Deformation Zone, the upper boundary of unit P1 is characterized by structural truncation. Here, undisturbed Oligocene strata rest unconformably on folded P1 strata of Eocene age. The boundary between units P1 and R1 therefore represents a tectonically enhanced unconformity. Also, Vandenberghe *et al.* (1995) relate the sequence boundary at the top of the Zelzate Formation onshore to tectonic uplift.

Oligocene

*Rupelian Units R*1 *and R*2

Unit R1, which rests unconformably on P1, probably correlates with most of the Niel Formation of Belgium, recently defined by Steurbaut (1992) and consisting of shallow-marine to deltaic/estuarine sands and clays. The irregular and laterally discontinuous seismic facies of R1 is consistent with this type of deposits (Table 1; Fig. 12). On the seismic data, the upper boundary of unit R1 is marked by erosional truncation. Therefore, it could be interpreted as a sequence boundary, but it could also be correlative with the transgressive surface identified by Vandenberghe *et al.* (1995) at some metres below the top of the Niel Formation.

The overlying unit R2 is the youngest Palaeogene sedimentary unit in the study area. It reaches a maximum thickness of about 60 m and represents the offshore equivalent of the (Rupelian) Boom Formation, better known as the 'Boom clay' of Belgium (Vandenberghe 1978). It possibly also includes the uppermost part of the Niel Formation. Two depositional sequences have been identified in the Belgian outcrops by means of grain-size analysis (Vandenberghe & Van Echelpoel 1987; Vandenberghe *et al.* 1995), but this could not be confirmed by the offshore seismic data. The seismic facies of the 'Boom clay' is very characteristic and consists of a very regularly banded pattern of parallel reflections (Table 1, Fig. 13). On very high-resolution seismic data, recorded slightly outside the study area on the Schelde river near Antwerp, Henriet *et al.* (1986) observed that these parallel reflections actually consist of alignments of numerous diffraction hyperbolae, generated by the well-known bands of Boom clay concretions or septaria.

Neogene and Quaternary

In the North Sea Basin, outside the study area, unit R2 is unconformably overlain by Neogene and Quaternary deposits (Balson 1989; Cameron *et al.* 1989). The unconformity separating them is a pronounced erosion surface (Fig. 13) with locally well-developed scour-hollows and valley profiles. It is very likely that at least part of this erosion surface results from the major and ubiquitous mid-Oligocene sea level drop (Haq *et al.* 1987).

Neogene deposits are missing in most of the offshore Belgian Basin, but do occur locally as outliers, filling scour hollows such as the Murray Pit (Liu *et al.* 1993). In the study area, there is a distinct angular unconformity and stratigraphic break between the Palaeogene and Late Pleistocene to Holocene sediments, the distribution and origin of which have been discussed by Liu *et al.* (1992; 1993) and others.

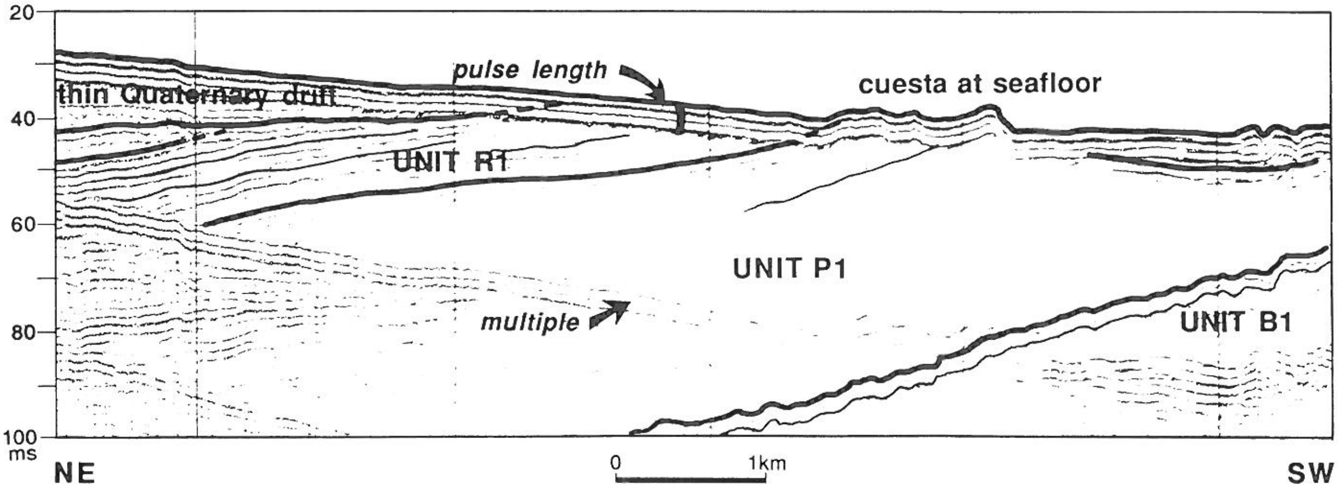

Fig. 12. Interpreted sparker section showing the seismic facies and outcrop characteristics of unit P1. See Fig. 2 for location.

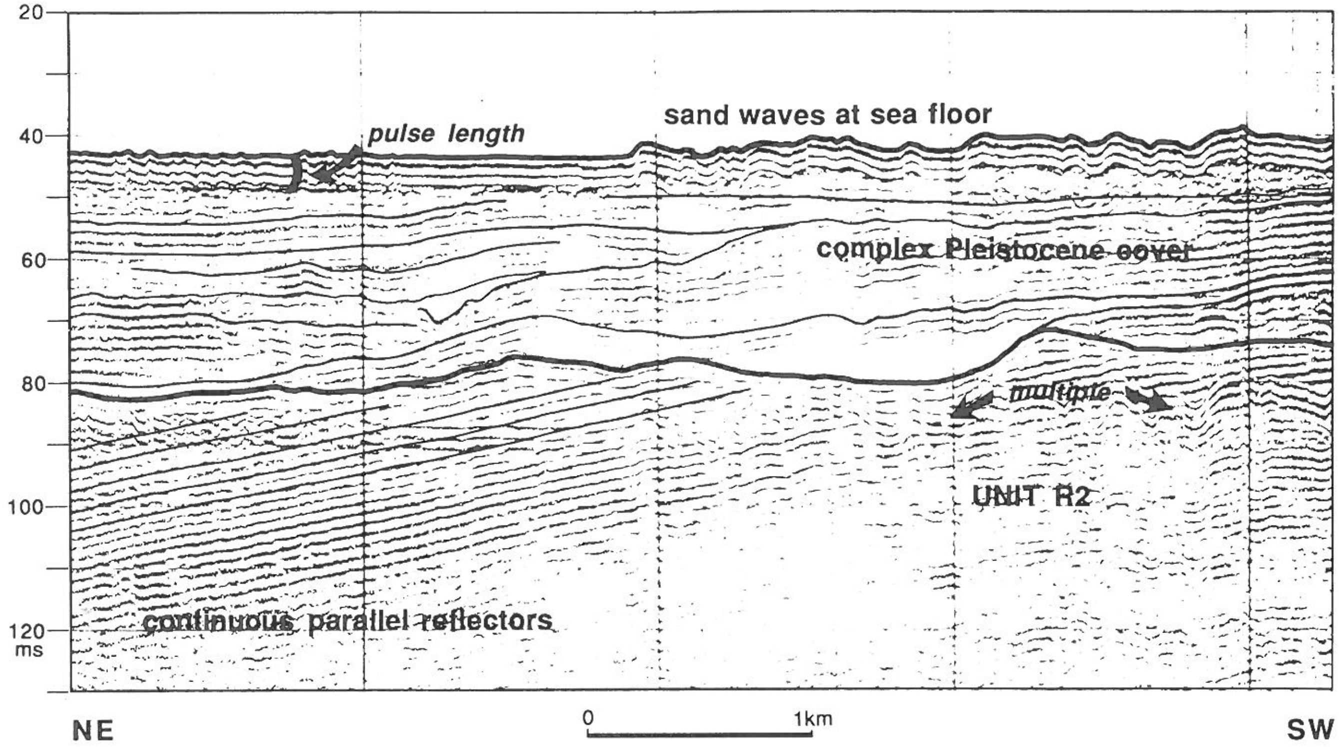

Fig. 13. Interpreted sparker section showing the characteristic seismic facies of unit R2 and the angular unconformity with the overlying Pleistocene (?) deposits. See Fig. 2 for location.

Conclusions

On the basis of interpretation of an extensive high-resolution seismic grid a detailed seismic stratigraphic model has been developed for the Palaeogene in the offshore Belgian Basin. Thirteen seismic units have been defined. Detailed analysis has allowed these units to be correlated with onshore deposits in NW Belgium (Fig. 7).

Three second order relative sea level cycles (transgressive-regressive cycles) have been inferred in the Palaeogene section. Peak second order transgressions (Ypresian, Lutetian–Bartonian, Rupelian) may have produced thick homogeneous clayey deposits, which are represented by unit Y1 (Kortrijk Formation), unit B1 (Maldegem Formation) and unit R2 (Boom Formation). During peak second order regressions (Thanetian, Late Ypresian, Priabonian, Rupelian) the development of erosional surfaces is enhanced. Examples of these could be the channel incisions of unit T2 (Tienen Formation) and unit Y4 (Vlierzele Member) and the major erosion surface at the top of unit R2 (Boom Formation).

These transgression–regression cycles do not all coincide with the second order eustatic variations of Haq *et al.* (1987). Long-term eustatic cyclicity may be overprinted by tectonic events, exerting a regional influence. Tectonically enhanced unconformities have been inferred at the base of unit T1 (Hannut Formation), of unit L2 (Lede Formation) and of unit R1 (Niel Formation). Of particular interest is the 2nd order eustatic sea level high that persisted during a large part of the Lutetian (Haq *et al.* 1987) and produced the main transgression in the Paris Basin. In the study area, this period is represented by a large hiatus, resulting from a major regressive phase accompanied by a tectonic pulse. Most probably, this phenomenon is related to the updoming of the Weald–Artois High and associated increase in sediment input.

When attempting a finer-scale sequence stratigraphic interpretation (third order) of high-resolution seismic data, it should be taken into consideration that the basic concepts of sequence stratigraphy, summarized by Van Wagoner *et al.* (1988), have been defined on a typical shelf-slope-basin section along an Atlantic-type continental margin. Their application to margins in a 'ramp-type setting', such as the Palaeogene southern North Sea shelf, is therefore not always straightforward, as pointed out by Vail *et al.* (1991). Some important differences with the general model could be observed in the study area and impeded the sequence stratigraphic interpretation.

(i) Geometries are less marked due to the low gradient and the distance from the shelf break. Consequently, systems tracts and sequences are stacked in a quasi parallel and conformable way, and sequences are separated by low-angle unconformities.

(ii) Due to the low gradient, ravinement during transgression (even on a parasequence scale) can be quite severe. Ravinement surfaces can therefore often be mistaken for subaerial erosion surfaces on seismic sections.

(iii) Sequences tend to be mainly composed of transgressive and highstand systems tracts, the lowstand deposits being preserved only as incised channel fills.

Future integration of more offshore borehole information is therefore required to validate our interpretations.

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