Timing and mode of Paleogene deformation on the Southern North Sea Cleaver Bank High and its relation to uplift of the British Isles

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TABLE OF CONTENTS

ABSTRACT

The aim of this project is to gain better constraints on the relative timing of uplift of the British Isles and Pyrenean shortening phase and to better understand the role of each in the Late Paleogene deformation on the Cleaver Bank High (CBH) and the southern North Sea in general. An exhaustive characterization of the stratigraphy and morphology of Late Paleogene deposits on the Cleaver Bank High area was carried out to make a differentiation between pre-, syn- and post-tectonic sedimentation. The analysis of seismic reflections geometry and seismic facies of regional 2D seismic lines of public access, along with well data, has allowed to identify and map a surface defining the onset of folding and estimate an age to it of Mid-Eocene, hence finding the probable time of salt tectonics initiation. Observations and evidence for gravity gliding as the driving force were used to conclude on the reigning type of deformation. The onset of folding was later used to guide a horizon flattening analysis to inquire for the first time in the southern North Sea into the plausible relationship of the southern British Isles uplift -and consequent basement tilt change- with the observed gravity gliding in the CBH area. The results showed a correspondence between the amount of exhumation of the southern British Isles with the stretching of Neogene deposits to the southwest and the basement dip change in some of the analyzed seismic lines. Given the close genetic relationship between the exhumation episodes and the tectonic phases from the Alpine collision, it is inferred that by the time the 'onset of folding' succession started to deposit the Laramide tectonic phase would have already acted and provided part of the total uplift, while the Pyrenean phase would have had a greater impact in providing the remaining amount of uplift necessary to finally reverse the basement dip from southwest to northeast and allow for imminent gravity gliding -and consequent folding- since Mid-Late Paleogene to present times.

INTRODUCTION

The Dutch North Sea area was affected by at least three different pulses of inversion since the Late Mesozoic, all attributed to the Alpine orogeny that results from the continent-continent collision between Africa and Eurasia. These three main compressional tectonic phases are the late Cretaceous sub-Hercynean, the Mid-Paleocene Laramide phases and the Pyrenean phase that took place around the Eocene–Oligocene boundary. Contemporaneously with the Laramide and Pyrenean phases, the British Isles underwent kilometer-scale exhumation. Their history of successive uplift/exhumation events during the Cenozoic (Figures 1 and 2) has resulted in a net change in tilt direction of the basement from the southwest to the northeast in the southern North Sea.

Halokinesis can result from gravity instability triggered by tilt of the basement and driven by gliding of the salt. As salt is very weak, the salt layer acts as a very efficient décollement between the basement and sedimentary overburden. This results in deformation with extension updip and contraction downdip (Fort and Brun, 2012).

Late Mesozoic and Cenozoic sliding of the post-salt cover in the North Sea (NS) region has been suggested due to a change of basement tilt attributed to Paleocene sediment loading and regional subsidence in the central North Sea (Bishop et al., 1995; and Stewart, 2007), but no linkage has been made with the uplift of southern Britain.

The significant amount of Zechstein salt in the southern NS, with an average thickness of ~700 m and sometimes reaching values as high as 1400 m on the Cleaver Bank High (CBH), played an active role in deformation, as witnessed by the presence of numerous salt swells or pillows. In terms of deformation of the Paleogene succession as observed today in the CBH, salt movement is generally attributed as the main reason. However the mechanisms leading to the instability of the salt layer can still vary from sediment loading, tectonic stress from sub-salt faulting (extension) or gravity (Thomson, 2006).

Therefore, any attempt on finding a relationship between the southern British Isles uplift and gravity gliding in the southern NS must first validate that in this region we are in the presence of a thin-skinned type of deformation. The analysis of the relation between supra- and sub-Zechstein faulting allows to discriminate between thick- and thin-skinned deformation.

By bringing together previous work in the southern NS Basin and using regional seismic lines across political boundaries this study aims to provide one of the few regional mapping and comprehensive synthesis on the time and mode of Paleogene deformation in this region. After analyzing separately the different components involved, they are combined into one single story in order to understand the real dynamics of the entire process. Seismic interpretation of long, regional lines focus at regional interrelationships among different components that may seem to have no connection when assessed only at a local level. In the present work, the Late Permian to Neogene succession of the CBH area has been analyzed based on the interpretation of key horizons. Special attention was paid to the onset of folding, for which lithostratigraphic markers from well data provided a good age constraint. The analysis of Cenozoic syn-kinematic deposits yields additional constraints on the timing of deformation.

Subsequently, the *flatten horizon* technique was used to recreate conditions at the moment of deposition of the recognized deformed succession to evaluate the evolution of the basement tilt through time. The regional seismic lines give insights to the process at a regional scale from the southeastern coast of England to the Dutch Central Graben. The results show that the uplift pulses of Britain can be correlated with the moments in which the basement changes dip. From the observed association in the timing of those elements the balance is tipped in favor of gravity gliding as the mechanism for halokinesis initiation.

1. GEOLOGICAL SETTING

A landlocked depression well below global sea levels developed in the Southern Permian Basin under an arid climate early during the Late Permian. With subsidence rates exceeding sedimentation rates, a catastrophic flood by saline sea-waters with cyclic evaporation resulted in the deposition of the thick halite-dominated Zechstein sequence (Ziegler, 1988, 1990).

Mesozoic, Kimmerian breaking-up of Pangea Rifting related to the Mesozoic break-up of the Pangea supercontinent commenced during the Triassic in the Arctic-North Atlantic and between Greenland and Scandinavia. By the Middle Triassic, the extension had reached the southern North Sea. Continued extension in the western rift branch resulted during the Middle Jurassic in continental breakup and the opening of the Central Atlantic Ocean (Ziegler, 1988, 1990).

The Cleaver Bank High (CBH), the Ameland Block (ALB) and the Schill Grund High platforms were uplifted and eroded (Figure 3) during the Middle Jurassic Central North Sea doming (Ziegler, 1990; De Jager, 2007).

Towards the end of the Early Cretaceous, crustal separation was achieved in the North Atlantic, and rifting began to concentrate on the area of the Norwegian and Greenland seas. During the mid-Cretaceous, extensional forces still prevailed in the North Sea basin area due to the opening of the North Atlantic. By the Late Cretaceous a completely different tectonic regime had started with the Alpine orogeny development as a result of the convergence between Africa and Eurasia (Ziegler, 1988, 1990). In many areas of the southern North Sea, the compressional stresses induced the inversion of Mesozoic extensional basins with uplift occurring continuously, albeit with several acceleration pulses (De Jager, 2003). Three pulses of inversion have been related to three different tectonic phases attributed to the Alpine collision: the Late Cretaceous sub-Hercynean, the Mid-Paleocene Laramide, and the Pyrenean phase that took place around the Eocene–Oligocene boundary (De Lugt et al., 2003).

As opposed to the surrounding basins of the southern North Sea that were strongly inverted during the Late Cretaceous-Paleogene Alpine convergence, the platforms such as the CBH, the ALB and the Schill Grund High (Figure 4 *a*) remained largely undeformed as evidenced by the remarkably continuous and regular Cretaceous to early Paleogene succession.

1.1 Cenozoic deformation of the Cleaver Bank High (CBH)

The Cenozoic deformation in the CBH must be related to a different process than Late Cretaceous basin inversion. Reactivation of the Zechstein salt is a mechanism that has unquestionably influenced the folding configuration of the post-salt cover in the CBH, where salt flow was minor and resulted only in the occurrence of salt swells or pillows. According to Thomson (2006) at least two models for the development of linear salt-cored swells within the southern North Sea have been proposed: 1) they were formed as a response to basement faulting and/or differential sedimentary loading; 2) Stewart and Coward (1995) proposed that the swells formed due to buckle folding, as a result of pre-Cretaceous regional tilting and consequent sliding of the post-salt cover towards the southwest. A subsequent reversal of the tilt during the Cenozoic uplifted the Sole Pit Trough, which experienced gravity spreading. This, together with loss of fault heave due to inversion in the pre-salt section, was balanced by growth of salt swells. In contrast to the first model, the second one does not require vertical shear within the fold limbs.

A variation on the thin-skinned deformation model was suggested by Bishop et al. (1995). They suggested that loading from considerable sedimentary deposition during the Jurassic and Early Cretaceous combined with regional tilting caused the supra-salt sequence to extend and slide under the force of gravity towards the northeast during the Late Cretaceous and Paleocene. The sharp increases in regional dip in the Paleocene were attributed to loading by the Paleocene delta and regional subsidence in the central North Sea to the east.

Using almost the very same concept, Stewart (2007) proposed that gravity and Zechstein salt played the roles of driving force and regional detachment, respectively, in two different areas in the central and southern North Sea. The author ascribed a Mesozoic peripheral extensional system encircling the southern area and regional tilt for thin-skinned gravity-driven sliding of the cover into the basin, with extension being reactivated on parts of this system in the Cenozoic. The fault system is analogous to extensional systems in updip domains of the circum-Atlantic salt basins, where there is kinematic linkage between thin-skinned extension and downdip thin-skinned compressional structures. At a large scale the detached extensional systems trend parallel to present-day top basement strike.

Backstripping results indicate that sub salt faulting in the southern North Sea occurred prior to the Late Jurassic and it was predominantly related to Early-Mid-Kimmerian extension (Abdul Fattah et al., 2012; Ten Veen et al., 2012). According to these authors, salt flow was minor on the platforms/highs during the major phases of Jurassic rifting as they experienced less structural deformation and Jurassic overburden was absent. Main salt flow was triggered during the Sub-Hercynian and later phases of compression resulting in salt pillow geometries. Coeval with the Alpine inversion phases, profound exhumation took place in the southern British Isles (Japsen 2000, Green et al. 2001; Green, 2005; Hillis, 2008; Holford et al., 2009; Cogné et al., 2016). Several techniques have been used to study Cenozoic uplift and erosion around the North Atlantic, from maximum-burial (e.g. Bulat and Stoker, 1987; Jensen and Schmidt, 1992; Japsen, 1998) and apatite fission-track analysis (AFTA) (e.g. Green et al. 2001; Green, 2005; Hillis, 2008; Holford et al., 2009; Cogné et al., 2016) to geomorphological (e.g. Doré, 1992; Riis, 1996; Lidmar-Bergström, 2000) and sediment-supply studies (Andersen et al., 2000; Clausen et al., 2000; Evans et al., 2000). AFTA data from across the British Isles by Holford et al. (2009) have shown that the main periods of time experiencing uplift are the Early Cenozoic (65–55 Ma), Mid-Cenozoic (40–25 Ma), and Late Cenozoic (20–15 Ma), indicating a close genetic relationship with key deformation events at proximal plate boundaries as a result of the Alpine collision. Whether the uplift is related to isostatic uplift caused by magma emplacement at the base of the crust (Rickers et al., 2013) or to regional compression of the lithosphere (Hillis, 2008) (to mention the most common), several authors (Japsen, 2000; Blundell, 2002; Hillis, 2008; Holford et al., 2009) agree that the main kilometer-scale exhumation events of the southern British Isles can be correlated to Alpine phases (Figure 1).

2. DATABASE

2.1 Seismic data

This study is based on interpretation of near fifty lines of 2D conventional reflection seismic data, which is non-confidential and has been kindly supplied by TNO's (Utrecht) petroleum geosciences group, Schlumberger's data management services, the British Geological Survey's enquiries department (www.bgs.ac.uk/enquiries), and/or downloaded from the UK Oil and Gas Data portal (www.ukoilandgasdata.com). The data set consists of lines from five different surveys (NSR, SNST83, SNSTI-NL-87, BIRPS, and OGA) and covers an area of roughly 54.000 km^2 with line spacing of between 10 and 25 km (Figure 4 *b*). Most lines are SE-NW or NE-SW oriented with lengths that vary from 50 to 400 km. They provide subsurface information of the southern North Sea Basin including (mostly) the offshore sections of the Netherlands and the UK to the northwest and east, respectively, with the Cleaver Bank High (CBH) area in the center. Non-confidential 3D seismic data from seven different surveys covering the CBH, supplied by TNO, was used for additional analysis and to complete missing sections of the 2D lines. Nonetheless, almost the total percentage of the results stem from the 2D seismic interpretation. The software used for all seismic interpretation was *Petrel 2015 release* by Schlumberger.

Since the seismic surveys were acquired by different companies and in different periods of time over the past few decades, some differences were encountered in resolution and polarity of the data. Therefore, it was first applied a so-called quality control (QC) that consists of verifying that all seismic data had the same phase (zero-phase of European polarity) and the application of time-shifts. Only for one set (NSR), a phase shift of 180° (polarity reversal) had to be applied. Minor time shifts were applied as well when necessary to obtain the best match between intersecting surveys. In addition to the QC, new composite lines were generated of the 2D lines that are composed of several shorter lines, notably from the SNST83 and OGA surveys. This action is important for the horizon flattening operation which gives better results for a single composite line than for several shorter ones.

The lines from the NSR, SNST83, SNSTI-NL-87, and OGA surveys were acquired using a 4 ms sampling resulting in high-seismic resolution profiles suitable for interpretation of shallower layers (e.g. Mesozoic and Cenozoic successions). However, the lines from the BIRPS survey were originally acquired to evaluate the very deep subsurface (up to 15 s two-way traveltime) using a 16 ms sampling. This derived in a much lower seismic resolution of the shallower layers due to the lower frequency content. Therefore, interpretation on the lines from the BIRPS survey was focused on the main reflectors of which the characteristic strong acoustic impedances allow for picking despite the poorer resolution (Base of the Zechstein Group (ZE), the Rijnland Group (KN), the Chalk Group (CK), and the North Sea Supergroup (N)).

2.2 Geological maps and velocity models

Surfaces in time (two-way traveltime or TWT) and depth (TVD) of the main lithostratigraphic layers from the Digital Geological Models of the deep subsurface of the Netherlands (DGM-deep) were used as a reference (for the Dutch sector) (Kombrink et al., 2012). These surfaces provide a reliable time constraint as they have been calibrated with data of over 1000 wells from the digital archive of Data and Information of the Dutch Subsurface (DINO).

Interval velocity (*V_{int}*) distribution maps of Velmod-2 (Van Dalfsen et al., 2006, 2007) for each layer (including the Zechstein), along with the surfaces in time, provided the means to build a velocity model for time-depth conversion in the Dutch sector (*Dutch* model). This layer-cake model which treats each lithologic unit separately is based on the linear function V_{int} (z_{mid}) = V_0 + K · z_{mid}, where the V_{int} and z_{mid} values stem from sonic logs and borehole deviation data. The surfaces and the V_{int} grids of the main stratigraphic units were downloaded from the NL Oil and Gas Portal (www.nlog.nl). More detailed information on the interval velocities calculation and Velmod-2 can be found in Van Dalfsen et al. (2006, 2007).

No well data and hence no V_{int} grids were available for the British sector, therefore a second model was built (*British* model) using the *Dutch* model as a basis. The *British* model was built using the same V_{int} grids of each layer (except for the Zechstein) that were used for the *Dutch* model. The grids were assigned to the generated surfaces from horizon interpretation, previously clipped for the British sector. The Zechstein sequence (base and top) was interpreted in the British sector and a constant velocity was assigned to it. Because the different lithologies of the Zechstein Group (mainly halite and carbonates) are not affected by compaction, the layer can be modelled using a constant interval velocity of 4500 m/s. In the end, both the *Dutch* and *British* velocity models work independently. The first one was used for time-depth conversion of all maps except for the Zechstein map which stems from a combination of both models.

2.3 Well data

Depth markers from almost 50 wells in the Dutch territory on top or nearby the interpreted 2D seismic lines (Figure 4 *b*) were used to time-constrain the interpreted horizon that marks the onset of folding (to be introduced in the next chapter). Almost 75% of those wells delivered more accurate information due to an increased proximity of the horizon to certain markers. These wells have been tied to seismic through check-shot data, thus providing depth markers of the different stratigraphic units as defined in the DINOloket data portal of the Geological Survey of the Netherlands (www.dinoloket.nl/nomenclature-deep), in which age control is mainly based on previous biostratigraphic studies.

3. METHODS AND RESULTS

3.1 Horizon interpretation

A total of seven seismic horizons comprising the Late Paleozoic, Late Mesozoic and Cenozoic successions of the southern North Sea basin have been interpreted in the study area. These seismic reflectors, some of which correspond to regional unconformities, subdivide the succession into different seismo-stratigraphic units, each with its own seismic signature.

Two different nomenclatures exist to describe the Dutch and British lithostratigraphy of the North Sea (Figure 5). In the present work the Dutch nomenclature has been preferred over the British one since most of the study area and the CBH, one of the focal points of the study, are predominantly in Dutch territory. According to the main lithostratigraphic layers of the Netherland's subsurface five of the interpreted horizons correspond to: Base Zechstein Group (Permian), Base Rijnland Group (Lower Cretaceous), Base Chalk Group (Upper Cretaceous), Base Lower North Sea Group (Paleogene), and Base Upper North Sea Group (Neogene).

The Base Zechstein was interpreted to study the development in time of the basement. In addition, the Top Zechstein was interpreted only in the British sector. Top and Base Zechstein were used as input for building the velocity model for the British sector (*British* model).

As mentioned before, sufficient control from well data exists for the Dutch sector of the study area, however this was not the case for the British sector where no well data was available. Therefore, interpretation in the latter was carried out based on correlations between intersecting seismic lines from each sector and complemented with constraints from the literature (Cameron and Ziegler, 1997; Japsen, 2000; Doornenbal et al., 2010).

3.1.1 Base and Top Zechstein Group (ZE) (Upper Permian)

It was earlier noted that the Base ZE was interpreted to allow the analysis of the basement development through time. This is because in the present work the 'basement' is taken to be the Base of the Zechstein Group, which is commonly recognized as a strong reflector on seismic reflection data. The Base ZE was the only horizon interpreted to the very extent of all the available seismic lines due to its ubiquitous continuity. It is clear that interpretation reaching furthest into the southeast sector of the UK plays a key role if any connection is to be verified between the British Isles uplift and a basement tilt change.

In addition to the Base, the Top ZE has also been interpreted (only in the British sector of the study area) with the purpose of delimiting the whole ZE succession and subsequently assign to it a constant velocity in the velocity modeling process. The Top ZE is interpreted on the basis of its high amplitude and the clear difference in seismic facies with the supra-Zechstein. It also coincides in most occasions with other horizons such as the Base Triassic or the interpreted Base Cretaceous. The characteristic 'transparent' seismic facies of halite facilitates the identification of the Top (and Base) ZE, marking a big contrast with the seismic facies of the overlying successions generally represented by continuous reflectors of Triassic or Cretaceous deposits.

3.1.2 Base Rijnland Group (KN) (Lower Cretaceous)

The Base KN is imaged as a fairly continuous reflector of medium amplitude. It is the least obvious of the interpreted surfaces and its identification is mostly based on well control from the Dutch sector and subsequent correlation into the British sector. The Base KN surface has undergone most erosion in the study area with respect to all interpreted horizons, naturally excluding the missing Triassic and Jurassic in the CBH that were not interpreted. The Base KN erosion can be evidenced in its depth map (Figure A-1 of the Appendix), including zones of the Elbow Spit High, the inverted Dutch Central Graben and a few salt walls. Toward the west the surface is recurrently truncated by the Base CK, in particular across the Indefatigable Shelf and east of the Sole Pit Basin (Figure 6 and Figure 7 *a*) where Lower Cretaceous sediments of the Rijnland Group are absent due to periodic inversion that began in latest Jurassic times (Cameron et al., 1992).

3.1.3 Base Chalk Group (CK) (Upper Cretaceous)

The Base CK reflection has smaller amplitude values than the Base of the Lower and Upper North Sea Groups reflections. However, the Base CK reflector is strong enough to be traceable throughout the entire study area. Chalk deposits (as well as Lower Cretaceous deposits of the KN Group) show depositional thinning and truncation by the Base Upper NS Group towards the inversion zone of the Dutch Central Graben (Figure 8). Depositional thinning is also observed toward the southwest where the Base CK (Base Cretaceous Unconformity) itself truncates Jurassic and older sediments (Figure 6 and Figure 7 *b*). The seismic facies of the thick Chalk succession that predominantly consists of carbonate rocks, is characterized by medium amplitude, medium frequency, and above all parallel and continuous reflectors (Figure 7 *a*, *b* and *c*).

3.1.4 Base Lower North Sea Group (NL) (Paleogene)

The Base NL (also base of SU 1 in this study) is predominantly imaged as a continuous high-amplitude reflector that divides two distinct seismic facies: the Early and Middle Paleogene siliciclastic succession of SU 1, above, and the Cretaceous carbonates of the Chalk Group (CK), below.

It is a conformable surface throughout most of the study area (e.g. Figure 7 *b, c* and *d*), except for parts of the Dutch Central Graben where the underlying succession of the Chalk Group (and sometimes the Rijnland Group) is truncated (Figure 8). Paleogene deposits of the Lower North Sea Group have been eroded towards the west where they are truncated by the Base of the Upper NS Group regional unconformity (Figure 6 and 7 *c*).

3.1.5 *Onset of folding (oof)* (Mid Eocene)

An unconformity has been identified between the Base of the Lower and Upper NS Groups, with subcrop concordance and onlapping of overlying reflectors mainly above salt pillows (Figure 9 *inset*). This unconformity has been named as *onset of folding (oof)* since it represents the last surface to be deposited before start of deformation (folding) of the whole succession from this point until the Base Cretaceous. More on the *oof* surface and its importance for the present work will be elaborated in the discussion chapter.

This surface imaged as a low-medium amplitude reflector has been initially recognized on lines of SW-NE orientation across the CBH in which its amplitude appears to have maximum values. Interpretation towards the west of the study area, where amplitude diminishes, relies mostly on thickness preservation of the seismo-stratigraphic unit defined by the surface itself and the Base of the Lower NS Group (i.e. SU 1). It is as well the first surface of all interpreted horizons to be truncated by the Upper NS Group regional unconformity as one move toward the west (Figure 6 and 7 *d*). For this reason, the *oof* depth map appears as the smallest in terms of surface area when compared to the other surfaces' depth maps (Figure A-4 of the Appendix).

The *oof* surface was analyzed with the available well data and depth markers on top or nearby the interpreted 2D seismic lines. It was observed that the surface is consistently below the marker of the Middle NS Group Rupel Formation (NMRF) of age Late Eocene to Early Oligocene (Priabonian to Rupelian) -or sometimes just below the Middle NS Group (NM)- and above the marker of the Lower NS Group Ieper Member (NLFFY) of age Early Eocene (Ypresian) (Figure 10) (www.dinoloket.nl/nomenclature-deep). A better constraint is given by two markers of the Lower NS Group, the Asse Member (NLFFB) of age Lutetian to Bartonian and the Brussels Marl Member (NLFFM) of age Middle Eocene, since the *oof* surface was in almost 75% of the total well population within ~200 m of either marker. Therefore, the age of the *oof* surface has been determined to be Middle Eocene (Lutetian).

The *oof* surface separates seismo-stratigraphic units SU 1 at the bottom and SU 2 at the top, between the Base NL and the Base NU. SU 1 represents the NL Group succession (Late Paleocene to Middle Eocene) comprising an alternation of sandstones and clays that derive from several small- and large-scale, clastic sedimentation cycles in a marine realm along the edge of the North Sea Basin (Van Adrichem Boogaert and Kouwe, 1993 - 1997). SU 2, mainly composed of rocks of the NM Group consisting of sands, silts and clays of a predominantly marine origin (Van Adrichem Boogaert and Kouwe, 1993 - 1997), is characterized by medium-high amplitude, high frequency, parallel to sub-parallel, and fairly continuous reflectors. The seismic facies of SU 1 and SU 2 are similar except for the lower frequency and especially lower amplitudes of SU 1 (Figure 7 *d* and *e*, and Figure 9). The absence of truncation of underlying sediments is a distinct and ubiquitous characteristic of the *oof* surface.

3.1.6 Base Upper North Sea Group (NU) (Neogene)

The Base of the Upper NS Group (NU) rests unconformably on the Middle NS Group (NM) or older deposits. This unconformity of Miocene age is imaged as a continuous medium-high amplitude reflector. Overlying terminations are generally characterized by downlap to the eastern margin and over the Dutch Central Graben (Figure 8) and onlap over the CBH area (Figure 9 *inset*). The lower boundary of the Base NU is marked by truncation or toplap of underlying sediments only west of the study area (Figure 7 *c* and *d*), elsewhere plays the part of a conformable surface (Figure 7 *e* and 8).

3.2 Geological maps

All horizons have been subsequently gridded and interpolated to generate maps in two-way traveltime (TWT). Naturally, the accuracy of the maps diminishes at the external edges where the seismic data density is smaller, therefore the maps where clipped where data density along the edges is insufficient. As described in the previous section, erosion reduced the extent of especially the shallower surfaces and the base KN toward the west. The Neogene succession (NU) is thinning toward the west as well (Figure 6). Other zones of non-deposition/erosion that appear as blank spaces on the maps of the base CK, base KN (Figures A-2 and A-1 of the Appendix) and base ZE (Figure 11) are related to the Elbow Spit High, which was a high already during the Devonian (e.g. De Jager, 2007), and during the Late Cretaceous and Cenozoic Alpine inversion of the Dutch Central Graben.

Subsequently, the TWT surfaces were converted to depth using the *Dutch* velocity model (Van Dalfsen et al., 2006, 2007) (Figures A-1 to A-5 of the Appendix). The ZE map is the only depth map made from a combination of the *British* and *Dutch* velocity models (Figure 11).

Finally, the surfaces in depth were used to calculate thickness maps by subtracting the surfaces from each other and implementing true stratigraphic thickness (TST) to account for the existing folding and dipping reflectors (Figures A-6 to A-9 of the Appendix).

3.3 Horizon flattening

For the purpose of studying the evolution of the basement tilt in the southern North Sea basin, selected NE-SW oriented seismic lines have been analyzed across the Cleaver Bank High, and for the two available lines (*SNST83-7* and *SNST83-6A*), across the Indefatigable Shelf and up to the limit of the Sole Pit Basin (Figure 4 *a*). The NE-SW orientation is roughly parallel to the current basement tilt of the southern North Sea (Figure 11).

Each line has been flattened to the time value representative of the average time at which the *oof* surface and the base Cretaceous (Base KN or Base CK for the longest lines) are observed and mapped in the seismic. These two horizons have been chosen for the analysis as they comprise the rock successions that were once deposited in a relatively flat environment and subsequently deformed under the action of gravity gliding. The importance of the *oof* surface for the flattening operation becomes clear since it sets the crucial time level after which deformation would have started due to salt movement in response to a basement dip change.

The analysis of seismic lines further north of line *SNSTI-NL-87-07a* did not provide useful results because sedimentation in this area has been influenced by the Mid North Sea High (Figure 4 *a*). Hence in lines such as *SNSTI-NL-87-06a* the basement dips to the southwest in all profiles, before and after horizon flattening (Figure A-10 of the Appendix).

The analysis of seismic lines further south of line *SNST83-6A* was also attempted without good results due to the presence in such lines of salt walls of considerable thickness (from around 2000 m to 4000 m), which have clearly affected all supra-ZE deposits up to the Base NU. Such major deformation of the base Cretaceous and the *oof* horizon precludes the use of an average surface depth for the flattening procedure.

By flattening the surfaces it is assumed that deposition occurred on a flat, non-tilted, sea bottom, a reasonable assumption since rising sea levels during the Early Cretaceous led to open-marine deposition (fines and carbonates) settled from suspension in the southern North Sea Basin.

Furthermore, Upper Cretaceous chalks are found over large areas of the earth's surface and reflect relatively stable and uniform conditions during a long period of time.

Both the original and the flattened seismic lines in two-way traveltime (TWT) have been converted to depth using the respective generated velocity model depending on which sector -*Dutch* or *British*- each line sits. The depth profiles favor a more realistic interpretation of the results and provide a rough reference in meters that can be compared to evidence in the literature related to the exhumation of the British Isles. Therefore, a total of six seismic profiles are presented for each line: non-flattened seismic profiles in a) TWT, and in b) depth; flattened seismic profiles at the *oof* surface level in c) TWT, and in d) depth; and flattened seismic profiles at the base Cretaceous level (KN or CK) in e) TWT, and in f) depth. The scale and vertical exaggeration are constant for each seismic line to facilitate comparisons.

The contrast between profiles in time and depth is also good to understand the *real* look of the ZE Group in the subsurface. Salt bodies usually have higher seismic velocities than the overlying sediments making seismic waves travel faster through them. This renders the ZE succession in TWT sections shallower than it really is.

The last step in the horizon flattening operation consisted in interpreting the Base ZE (top 'basement') both in time and depth to attain some insight on the basement tilt in the southern NS Basin at two different times in geological history. This provides information on how it has evolved since the Early or Late Cretaceous to present day. As a measure for QC the interpretation in time of the Base ZE for the two flattened horizons was crosschecked with the flatten horizon option in Petrel which places automatically in the right position all interpreted horizons below the one being flattened.

It must be mentioned that the horizon flattening procedure may not be as accurate as for example structural balancing, which can incorporate sediments removal via decompaction technique and isostatic adjustment. However for the study area which is not very complex in terms of structural geology it represents a valid, straightforward way of looking to the geological history. One evident artifact that is introduced into the flattened sections is what could be described as a *mirror effect* from the salt pillows and rim synclines. This results in a deviation of the underlying reflectors (including the Base ZE of interest) of the same magnitude as the salt bodies. However the overall trend of the dip analysis is not affected and due to ease of detection it can be effectively tackled by drawing a mean line for the interpreted Base ZE.

The results and observations arising from the analysis of each seismic line from north to south are presented below.

3.3.1 Line *SNSTI-NL-87-07a*

The profiles of line *SNSTI-NL-87-07a* (Figures 12 and 13) go approximately from the western limit of the CBH to the start of the Central Graben (Figure 4 *a*). The non-flattened profiles (Figures 12 *a* and 14 *a*) show a northeast dipping basement that only becomes evident after reaching the Central Graben (CG) and that looks mostly flat for the CBH, even with the applied vertical exaggeration. This is the first line to show a basement tilt change, although very subtle, between the non-flattened and flattened sections. The profile flattened at KN in depth (Figure 13 *c*) shows a southwest dipping basement with a total depth difference of ~1 km between base and top of the mean (dashed) line for most of the CBH, which is reduced to ~700 m in the profile flattened at *oof* surface (Figure 13 *b*).

3.3.2 Line *SNSTI-NL-87-09a*

Like the previous one, line *SNSTI-NL-87-09a* (Figures 14 and 15) runs from the western edge of the CBH near the Indefatigable Shelf up to the start of the CG (Figure 4 *a*). For the non-flattened profiles (Figures 14 *a* and 15 *a*) it is more evident that the top basement is dipping to the northeast across the whole length of the seismic line if compared to line *SNSTI-NL-87-07a*. A mean line (dashed) drawn on the flattened depth sections (Figure 15 *b* and *c*) helps once again to see the real trend of the basement tilt past the numerous artifacts from salt bodies. The depth difference between base and top of the mean lines is similar for the two flattened profiles. The value of the flattened Base KN (Figure 15 *c*) is ~1.2 km which is circa 100 m greater than the value of the flattened *oof* surface (Figure 15 *b*). These depth difference values are also greater than the ones calculated for the same flattened profiles in line *SNSTI-NL-87-07a*

3.3.3 Line *SNST83-7*

Line SNST83-7 (Figures 16 and 17) is the longest line interpreted in the present work and possibly provides the best insight in the basement evolution across the southern North Sea from the southeast of England to the Dutch Central Graben. Unfortunately, this line could not be interpreted completely due to truncation of the Base Cretaceous (Base CK) by the Upper North Sea Group. The same applies for the *oof* surface, which flattened profiles logically provide information only for the interval where the surface is observed and not beyond the point where the surface is truncated by the Upper North Sea Group toward the west (Figures 16 *a* and 17 *a*).

In the non-flattened profile in time (Figure 16 *a*) there is an overall northeast dipping trend of the basement. However, the non-flattened profile in depth (Figure 17 *a*) only shows a northeast dipping trend of the basement for the CBH and CG sections. There is a trough (Sole Pit Trough) at the Base ZE level of ~1 km near the Sole Pit Basin/Indefatigable Shelf boundary. The through is also noticeable in the Base ZE depth map (Figure 11) and makes the basement tilt appear to be southwest dipping.

A net southwest dipping basement is observed in both depth-converted flattened profiles (Figures 17 *b* and 17 *c*). The depth differences between base and top of the mean (dashed) lines are much greater than those of the previous lines, with the profile flattened at CK level (Figure 17 *c*) having ~3.6 km and the profile flattened at the *oof* surface(Figure 17 *b*) around one kilometer less (~2.6 km).

3.3.4 Line *SNST83-6A*

Like line *SNST83-7*, line *SNST83-6A* (Figures 18 and 19) was interpreted until the truncation of the Base Cretaceous and the *oof* surface toward the west. The non-flattened depth profile (Figure 19 *a*) shows deepening of the base ZE towards the Sole Pit Trough as in line *SNST83-7*. Due to being shallower the basement tilt has an overall northeast dipping trend.

A net southwest dipping basement can be observed in the depth-converted and flattened profiles (Figures 19 *b* and 19 *c*) once again. The depth difference between base and top of the mean lines is slightly smaller than that of the previous line for the profile flattened at CK level (Figure 19 *c*), which in this case has a depth difference of ~3.3 km. For the profile flattened at the *oof* surface (Figure 19 *b*), though, the difference is ~1.3 km, half the value of the previous line.

3.4 Fault Interpretation

Several faults were interpreted along the different seismic lines. Understanding the main structural framework in the area and subsequent fault interpretation are key elements for horizon interpretation. The Paleogene succession of the Cleaver Bank High area is not particularly faulted. However, gravity gliding-related faulting is recognized in a few seismic lines of which some of the most relevant examples have been studied in more detail (Figure 20). Dating the syn-kinematic deposition along these faults provides additional information on the timing of salt movement.

Across most faults, the thicknesses of the Cretaceous (Lower and Upper) successions are very similar in both the hanging wall and footwall, indicating that these faults displacement occurred after the Cretaceous (possibly reactivated pre-Cretaceous faults). In Figure 20, cases *b* shows syn-kinematic deposition of Lower North Sea Group sediments (Lower-Mid Paleogene), confirming that by this time the faults were active. In case *c* the fault throw on both faults is too small to draw conclusions.

On the other hand, in cases *a* and *d* the main faults affect the complete Paleogene succession beyond the *oof* surface, plus the base of the Neogene, as indicated by the off-set base Neogene reflector and syn-kinematic Neogene deposition in the hanging wall of Neogene deposits. Syn-kinematic deposition of Lower-Mid Paleogene sediments is also observed in cases *a* and *d*, confirming like for the previous three cases that by this time the faults were active. There is apparent thinning of Cretaceous sediments as well in the hanging wall of cases *a* and *d* as a result of the normal faulting.

The secondary, smaller off-set faulting observed in most cases resemble the small extensional faults described by Stewart (2007). These associated faults are commonly arranged in a radial pattern that may develop as a result of crestal collapse of a salt diapir due to dissolution or differential compaction above the salt structure.

Previous authors have already presented evidence for thin-skinned deformation in the southern NS and the CBH area (Bishop et al., 1995; Stewart, 2007; Ten Veen et al., 2012). Nonetheless, in the present work the study area is analyzed with the available seismic lines in search of a link between the salt cover and basement faults (that would proof otherwise). Figure 20 shows the most outstanding cases of faults in the overburden in which no clear connection of faulting beneath and above the salt is observed. This could be explained by the thickness of halite in the area which is above 300 m in each case of Fig. 20.

A Zechstein thickness map of the Dutch offshore with the outline of the CBH also validates the significant presence of salt in this area (Figure 21), especially for the northern section where thickness values reach up to 1500 m.

3.5 Salt structures between the CBH and the Dutch Central Graben

In the chapter of geological setting it was introduced how during the Late Cretaceous the CBH was not affected by the Alpine inversion-related uplift, as opposed to the surrounding Mesozoic basins. The Alpine inversion in the Dutch Central Graben (DCG) resulted in depositional thinning and erosion of the Upper Cretaceous chalk and Lower Cenozoic clastics and in local truncation of older sediments (Ziegler, 1988, 1990) (Figure 8). Accordingly, the transition from the platform (high) to the basin is not smooth. The northeast dipping basement reaches maximum depth values at the boundary between the CBH and the DCG and thick successions of older rocks such as Triassic and Jurassic make a sudden appearance. Therefore it would be reasonable to expect some reaction of the salt as it moves downslope from the CBH to the DCG under the effects of gravity.

Five different profiles of NE-SW oriented seismic lines (roughly parallel to the basement dip) have been analyzed connecting the CBH and the southern edge of the DCG (Figure 22). The analysis is focused right at the frontier between the two structural elements where all different units from the Base ZE to the Neogene have been interpreted. The results are quite interesting; we observe in each case of Fig. 22 that salt structures of considerable amplitude have systematically formed. These salt structures are independent from one another and appertain to a repetitive pattern observed along the whole western margin of the DCB (Figure 21). In profiles *b.* and *c.* of Fig. 22 the salt structures have a thickness of circa 1500 m - 1800 m. The salt diapir to the right of profile *a.* is approximately 3200 m thick. Similar extrusion of salt bodies has been described in the Atlantic passive margins of Brazil, west Africa and east Canada where gliding of the salt oceanwards led to progressive thickening of the salt layer in the downdip part of the margin (Kidston et al., 2002; Brun and Fort, 2004; Rowan et al., 2004; Fort et al., 2004; Hudec and Jackson, 2006)

4. DISCUSSION

4.1 Age of the '*onset of folding' (oof)* surface and start of salt movement

From the analysis of seismic lines across the Cleaver Bank High it was observed that the Cretaceous - Paleogene succession of this area remained undeformed until the Mid-Late Paleogene, when a short phase of folding deformed the supra-Zechstein salt succession by décollement along that salt. The upper boundary of this succession is marked by a low-amplitude imaged surface named as *onset of folding (oof)*. Detailed analysis of the units below and above this surface based on seismic reflections geometry and seismic facies has allowed to interpret it across the whole study area up until truncation by the Base NU (Neogene) to the west. A complete succession of sediments that were once deposited on a flat, non-tilted, sea bottom has been effectively isolated assuming that the *oof* surface marks the limit between pre- and syn- or post-tectonic sedimentation. The start of salt movement can be inferred by determining the age of the surface, which has been estimated to be Middle Eocene (Lutetian) from the study of lithostratigraphic depth markers from circa 50 wells that have been tied to the seismic through check-shot data (www.dinoloket.nl/nomenclature-deep).

The syn-kinematic deposition analysis of halokinesis related faulting in the overburden (Figure 20) indicates that the earliest these faults became active (and hence start of halokinesis) was in the Early-Mid Paleogene, which is in agreement with the age calculation for the onset of folding. A couple of cases showed also that the faults may have been active as late as during the Late Paleogene and Early Neogene. Salt flow was more intense during periods that coincide with known tectonic phases and based on backstripping analysis on platform areas, such as the Cleaver Bank High, main salt flow was triggered during the Sub-Hercynian and later phases of compression (Abdul Fattah et al., 2012; Ten Veen et al., 2012). This includes the Late Paleogene Pyrenean and Early Neogene Savian phases (Figure 5).

4.2 Gravity gliding in the southern North Sea

Previous work in the southern North Sea have shown that gravity gliding was the mechanism responsible for deformation of Cretaceous and Paleogene sediments (Bishop et al.,1995, and Stewart, 2007). These authors coincide on the main phase of loading, tilting and resultant extension of the supra-salt sequence taking place during the Late Mesozoic and Cenozoic, coinciding with our first findings in terms of timing of salt movement.

From the fault interpretation in the Cleaver Bank High (CBH) and the analysis of seismic profiles at the boundary between the CBH and the Dutch Central Graben (DCG) additional evidence has been observed to support the presence of gravity gliding in the area. According to the observations in Figure 20 there is not a clear connection between faulting beneath the salt and in the overburden which indicates thin-skinned deformation. Due to the presence of a very thick salt layer there is no direct spatial relationship between faulting in the sub- and supra-ZE salt. This is true for the southern North Sea where basement (sub-salt) faulting was pervasive but cut through the Permian salt only on the basin margin and in the Central Graben (Coward and Stewart, 1995).

The formation of salt structures at the boundary between the CBH and the DCG (Figure 22) are hard to explain if not by salt sliding under the force of gravity and thickening after reaching a downslope peak and a sharp rock composition contrast composed of older rocks. These successions in the DCG stem from the broad uplift of post-salt deposits and significant erosion down to Jurassic sediments as a result of the Alpine inversion-related uplift that started in the Late Cretaceous. Bishop et al. (1995) concluded that there was a net flow of salt down-dip through time in the southern North Sea based on their section restorations. This phenomenon has been observed elsewhere in the world whenever there is a thick salt succession and sufficient tilt to trigger salt instability such as in the Atlantic passive margins of Brazil, west Africa and east Canada (Kidston et al., 2002; Brun and Fort, 2004; Rowan et al., 2004; Fort et al., 2004; Hudec and Jackson, 2006). The salt structures observed in Fig. 22 also resemble those described by Stewart (2007) for the 'downdip compressional domain' in the central and southern North Sea.

4.3 Temporal relation between the uplift of the southern British Isles and the onset of folding in the CBH

One of the main goals of the present work is to investigate on the possible link of the southern British Isles uplift and consequent basement tilt change with the observed gravity gliding in the CBH area.

The horizon flattening technique has been used to recreate the approximate original conditions of deposition of the succession between the Base Cretaceous and the 'onset of folding' (*oof*) surface. From the analysis on four seismic sections (Figs. 12-19) it is observed that the effect on the basement tilt increases from north to south. A lower degree of the basement tilt in the *oof* flattened profiles with respect to the Base Cretaceous (CK or KN) flattened ones has also been observed in each section. This indicates that the basement tilt would have been closer to switching from southwest to northeast dipping by the time the 'onset of folding' succession started to deposit. The southwest dipping basement during the Cretaceous observed in the flattened sections has been documented before (Coward and Stewart, 1995). According to these authors rift flank uplift on the edge of the Broad Fourteens and Central grabens prior to the Cretaceous, in combination with subsidence across the Dowsing - South Hewett Fault Zone (Figure 4 *a*), generated a basin slope from northeast to southwest (Sole Pit Trough).

Exhumation rates have been estimated from apatite fission-track analysis (AFTA) and stratigraphic data for the southern British Isles including areas of the southern NS Basin, Sole Pit High, East Midland Shelf, and Wessex Basin (Japsen 2000, Green et al. 2001; Green, 2005; Hillis, 2008; Holford et al., 2009). The exhumation rates vary from 0.5 to 2.5 km and took place during episodes in the Early-Mid Cenozoic (Figs. 1, 2 and 5). The depth differences between base and top of the Base ZE mean lines for the Cretaceous flattened profiles in lines *SNSTI-NL-87-07a* (Fig. 13 *c*) and *SNSTI-NL-87-09a* (Fig. 15 *c*) are ~1 km and ~1.2 km respectively, therefore in the same order of magnitude as the exhumation rates values. However, the depth differences for the longer lines *SNST83-7* (Fig. 17 *c*) and *SNST83-6A* (Fig. 19 *c*) are above the highest estimated exhumation rate by approximately one kilometer in both cases. One possible explanation for the higher differences could stem from the presence of the Sole Pit Trough which renders the basement at this zone ~1.5 km deeper than the surrounding average (Figures 4 *a* and 11). This local trough has also been identified by Stewart (2007) and Doornenbal et al. (2010) in their mapping efforts of the Base ZE for the same area, however their results showed depth values of circa 1 km shallower with respect to this work. Therefore, it is possible that the *British* velocity model used for this sector did not work properly at this particular location delivering greater depth values than the actual, one of the drawbacks and risks of generating a velocity model without well control.

The total amount of thinning of Neogene deposits towards the southwest (Figure 6) has been estimated to be ~1 km from Figs. 13 *a*, 15 *a*, 17 *a*, and 19 *a*. This stretching is in the same order of magnitude of the exhumation rates indicating that the British Isles uplift led to less accommodation space for Neogene sediments deposition to the southwest of the southern NS.

A correspondence between the exhumation of the southern British Isles and the basement dip change since deposition of Cretaceous sediments has been observed in some of the analyzed seismic lines with the horizon flattening technique. The same applies for the total amount of stretching of Neogene deposits to the southwest. At the same time, the flattened profiles at the *oof* surface showed that for the time of surface's deposition the basement was still dipping to the southwest but with a degree that is closer to the horizontal. Therefore a posterior, last pulse must have taken place before reversal of the basement dip. Figure 5 summarizes all the observations related to timing of uplift of the British Isles, tectonic phases of the Alpine collision and start of salt movement according to the interpretation and age estimation of the *oof* surface. It has been previously noted that the main kilometer-scale exhumation events of the southern British Isles can be correlated with times when Alpine phases took place (Japsen, 2000; Blundell, 2002; Holford et al., 2009; Hillis, 2008). The estimated age of the *oof* (Mid-Eocene) places the surface right in between the Mid-Paleocene Laramide and the Late Eocene – Early Oligocene Pyrenean phases. This implies that by the time the 'onset of folding' succession started to deposit the Laramide tectonic phase would have already acted and provided part of the total uplift, which is confirmed by the observed differences of the Base ZE tilt between the flattened profiles at Base Cretaceous and *oof* surface. However, because such differences are not considerable it is inferred that the Pyrenean phase had a greater weight in providing the remaining amount of uplift necessary to finally reverse the basement dip from southwest to northeast (Figure 23). This change allowed for imminent gravity gliding as it has been earlier identified since Mid-Late Paleogene to present times.

The plausible relationship between the southern British Isles uplift, the basement dip change from southwest to northeast and gravity gliding in the southern North Sea Basin has not been addressed before in the literature despite being an argument that follows simple logic. It has been shown that even by using some of the most fundamental methods, such as integral seismic interpretation and horizon flattening, it is possible to achieve reasonable results in favor of this idea. Implications for the oil industry would certainly be important in terms of rethinking existing petroleum systems (e.g. hydrocarbon charge) with this new interrelationship in mind in an area where oil/gas exploration and production have a very long history.

The use of the horizon flattening technique alone and the lack of more seismic and well data (especially for the British sector) represent clear limitations in the outcome of the study. For this reason the application of different methods other than those used in the present work (e.g. structural balancing) and the incorporation of more data are strongly recommended to further develop the initial findings that have been presented here.

5. CONCLUSIONS

The southern North Sea Basin has been analyzed using regional 2D seismic lines to provide a regional mapping and comprehensive synthesis on the time and mode of Paleogene deformation in this region.

A complete horizon interpretation of the main lithostratigraphic units from the Late Paleozoic to the Early Cenozoic was done across the entire study area, from which depth and thickness maps were obtained.

A surface marking the limit between pre- and syn- or post-tectonic sedimentation was identified based on seismic reflections geometry and seismic facies within the folded Paleogene succession of the Cleaver Bank High (CBH). This allowed to isolate a complete succession of sediments from the Base Cretaceous to the Mid Paleogene that were deposited on a non-tilted sea bottom before being deformed by décollement along the Zechstein salt. The surface was named *onset of folding (oof)* and has an estimated age of Middle Eocene (Lutetian) according to well data.

Gravity gliding has been established as the mechanism responsible for halokinesis and subsequent folding of the Paleogene succession in the CBH area. Seismic interpretation has proven that there is no link between sub- and supra-ZE salt faulting indicating that the type of deformation of this region can be classified as thin-skinned. Additional evidence supporting salt sliding under the force of gravity towards the northeast (basement dip) stems from the formation of salt structures of significant magnitude at the boundary between the CBH and the Dutch Central Graben. Here the Base ZE -or top basement- slope reaches maximum values and there is a sharp contrast between younger and older successions from one structural element to the other.

Dating syn-kinematic deposition along gravity gliding-related faulting provided additional information on the timing of salt movement. Results showed that these faults were mostly active during the whole Paleogene but also in the Early Neogene.

The plausible relationship of the southern British Isles uplift and consequent basement tilt change with the observed gravity gliding in the CBH area was investigated using regional 2d seismic lines and the horizon flattening technique. This way the approximate original conditions of deposition of the previously isolated succession between the Base Cretaceous and the *oof* surface were recreated. The results from this analysis showed that the basement tilt was dipping to the southwest by deposition of the Cretaceous and that there is a correspondence between the amount of exhumation of the southern British Isles (0.5 to 2.5 km) and the basement dip change in some of the analyzed seismic lines with the flattening operation (approx. 1 to 1.2 km). There is an additional correspondence between the exhumation rates from the literature and the amount of thinning of Cenozoic deposits (~1km) toward the southwest of the southern North Sea.

At the same time the flattened profiles at the *oof* surface showed that for the time of the surface's deposition the basement was still dipping to the southwest but with a degree that was closer to the horizontal, for which a later pulse must have taken place before final reversal of the dip. The *oof* surface (Mid-Eocene) sits between the Mid-Paleocene Laramide and the Late Eocene – Early Oligocene Pyrenean phases. Therefore it is inferred that by the time the 'onset of folding' succession started to deposit the Laramide tectonic phase would have already acted and provided part of the total uplift, but the later Pyrenean phase would have had a greater weight in providing the remaining amount of uplift necessary to finally reverse the basement dip from southwest to northeast. This change allowed for imminent gravity gliding in the CBH -and consequent folding- as previously identified since Mid-Late Paleogene to present times.

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FIGURE CAPTIONS

Figure 1. Cenozoic event stratigraphy diagram for the NW European Atlantic margin (Holford et al., 2009). The onset of cooling/exhumation episodes were identified from apatite fission-track analysis (AFTA) across the British Isles. The Cenozoic exhumation episodes can each be correlated with significant unconformities along the Atlantic margin, and they are also synchronous with tectonic movements along the Atlantic margin and major periods of deformation at proximal plate boundaries. IPU - Intra Pliocene unconformity; IMU - Intra-Miocene surface unconformity; BNU - Base Neogene unconformity; UEU - Upper Eocene unconformity; LEU - Lower Eocene unconformity; BPU - Base Paleogene unconformity.

Figure 2. Paleogeographic reconstructions of NW Europe (Holford et al., 2009) with superimposed patterns of vertical motions during the (B) early Cenozoic (65–55 Ma) and (C) mid-Cenozoic (40–25 Ma). Plus and minus symbols indicate areas undergoing uplift/exhumation or subsidence/burial, respectively, during the indicated time windows. BPU - Base Paleogene unconformity; UEU - Upper Eocene unconformity.

Figure 3. Burial graph of the Cleaver Bank High showing uplift of this platform area during the rifting from 160 to 80 Ma, and no indications of Late Cretaceous uplift (De Jager, 2007).

Figure 4. *a.* Structural elements map of the southern North Sea basin area showing Early Cretaceous (Hauterivian-132 Ma) main basins and highs (Doornenbal et al., 2010; completed with information from: Stewart, 2007; and Ten Veen et al., 2012). *b.* Network of interpreted seismic lines, names of the surveys and wells used for time-constraint of the mapped horizons.

Figure 5. Geologic time scale, stratigraphic correlation chart (UK and NL), mapped horizons and seismo-stratigraphic units, main tectonic deformation phases and onset of British Isles exhumation episodes (modified from Doornenbal et al., 2010; completed with information from: Kombrink et al., 2012; Praeg et al., 2005; Holford et al., 2009).

Figure 6. SW-NE oriented regional seismic line *(SNST83-6A)* from the Sole Pit Basin to the Central Graben showing all interpreted horizons and seismo-stratigraphic units. Note the truncation of Cretaceous (Upper and Lower) and Paleogene deposits (including the *oof* surface) towards the SW, as well as the thinning of Neogene deposits. For location see Fig. 4 *a*. 10x vertical exaggeration.

Figure 7. Inset figures from seismic line *SNST83-6A* (Fig. 6). Insets *a* to *d* correspond to the Indefatigable Shelf in the British sector while inset *e* corresponds to the Cleaver Bank High in the Dutch sector. 10x vertical exaggeration.

Figure 8. Section of seismic line *SNST83-6A* across the Dutch Central Graben. Note the downlapping of the Base NU's overlying terminations and depositional thinning of Cretaceous deposits (CK and KN) and truncation by the Base Lower NS Group (NL). For location see Fig. 4 *a*. 10x vertical exaggeration.

Figure 9. Seismic line *SNSTI-NL-87-05a* across the northern part of the Cleaver Bank High in the Dutch sector. *Inset:* detail of the *oof* surface and the characteristic onlapping of overlying reflectors above a salt pillow. For location see Fig. 4 *a*. 5x vertical exaggeration.

Figure 10. Depth markers with their respective measured depth values (meters) from wells F04-01, K07-02 and L01-02 displayed on two seismic lines (TWT) with horizon interpretation. Note the proximity of the *oof* surface to markers NLFFB and NLFFM. Location of the seismic lines, these three wells and the rest of the wells with depth markers used in the present work are shown on the map to the right.

Figure 11. Depth map (meters) of the base of the Zechstein Group (ZE). Faults (dark red) from Doornenbal et al., 2010. *Inset:* same map showing all seismic lines (red) where the Base ZE was interpreted and used for interpolation of the final depth map.

Figure 12. Horizon flattening analysis of seismic line *SNSTI-NL-87-07a* in **time (TWT)**. *a.* Non-flattened seismic profile. *b.* Flattened seismic profile at the *oof* surface level. *c.* Flattened seismic profile at the base Cretaceous level (KN). For location see Fig. 4 *a*. 7x vertical exaggeration.

Figure 13. Horizon flattening analysis of seismic line *SNSTI-NL-87-07a* in **depth (km)**. *a.* Non-flattened seismic profile. *b.* Flattened seismic profile at the *oof* surface level. *c.* Flattened seismic profile at the base Cretaceous level (KN). A dashed, white line represents the mean curve of the interpreted Base ZE. For location see Fig. 4 *a*. 7x vertical exaggeration.

Figure 14. Horizon flattening analysis of seismic line *SNSTI-NL-87-09a* in **time (TWT)**. *a.* Non-flattened seismic profile. *b.* Flattened seismic profile at the *oof* surface level. *c.* Flattened seismic profile at the base Cretaceous level (KN). For location see Fig. 4 *a*. 7x vertical exaggeration.

Figure 15. Horizon flattening analysis of seismic line *SNSTI-NL-87-09a* in **depth (km)**. *a.* Non-flattened seismic profile. *b.* Flattened seismic profile at the *oof* surface level. *c.* Flattened seismic profile at the base Cretaceous level (KN). A dashed, white line represents the mean curve of the interpreted Base ZE. For location see Fig. 4 *a*. 7x vertical exaggeration.

Figure 16. Horizon flattening analysis of seismic line *SNST83-7* in **time (TWT)**. *a.* Non-flattened seismic profile. *b.* Flattened seismic profile at the *oof* surface level. *c.* Flattened seismic profile at the base Upper Cretaceous level (CK). For location see Fig. 4 *a*. 7x vertical exaggeration.

Figure 17. Horizon flattening analysis of seismic line *SNST83-7* in **depth (km)**. *a.* Non-flattened seismic profile. *b.* Flattened seismic profile at the *oof* surface level. *c.* Flattened seismic profile at the base Upper Cretaceous level (CK). A dashed, white line represents the mean curve of the interpreted Base ZE. For location see Fig. 4 *a*. 7x vertical exaggeration.

Figure 18. Horizon flattening analysis of seismic line *SNST83-6A* in **time (TWT)**. *a.* Non-flattened seismic profile. *b.* Flattened seismic profile at the *oof* surface level. *c.* Flattened seismic profile at the base Upper Cretaceous level (CK). For location see Fig. 4 *a*. 7x vertical exaggeration.

Figure 19. Horizon flattening analysis of seismic line *SNST83-6A* in **depth (km)**. *a.* Non-flattened seismic profile. *b.* Flattened seismic profile at the *oof* surface level. *c.* Flattened seismic profile at the base Upper Cretaceous level (CK). A dashed, white line represents the mean curve of the interpreted Base ZE. For location see Fig. 4 *a*. 7x vertical exaggeration.

Figure 20. Five examples of late Paleogene faulting after start of salt movement in the CBH area, including all interpreted horizons and seismo-stratigraphic units. Both supra- and sub-ZE faults have been interpreted. Location of each figure and corresponding seismic line are displayed on the map at the bottom right. 5x vertical exaggeration.

Figure 21. Thickness map (meters) of the Dutch offshore Zechstein Group (ZE) with the outline of the Cleaver Bank High (CBH) and the Dutch Central Graben (DCG), and showing the location of seismic lines analyzed in Figs. 21 and 23.

Figure 22. Five different profiles on seismic lines connecting the CBH and the southern edge of the Dutch Central Graben, including all interpreted horizons and seismo-stratigraphic units. Note the formation of salt structures close to the boundary between the two structural elements. Location of the seismic lines and displayed sections are shown on the map at the bottom right. 5x vertical exaggeration.

Figure 23. Sketch of the temporal relation between the uplift of the southern British Isles and the change in basement tilt and onset of folding in the CBH. ***Bottom section:*** moment of deposition of the Base Cretaceous (145 Ma) on a non-tilted sea bottom. Basement at this time dips to the southwest. ***Middle section:*** moment of deposition of the *oof* surface (44 Ma) on a non-tilted sea bottom. Basement dips to the southwest with a degree closer to zero due to Southern British Isles uplift after Laramide tectonic phase (65-55 Ma). ***Top section:*** moment of deposition of the Base Neogene (23 Ma). By this time the Pyrenean tectonic phase (40-25 Ma) has completed reversal of basement dip from southwest to northeast and gravity gliding has commenced. Note how the thickness of the succession from the Base Cretaceous to the *oof* surface (Base SU 2) remains constant and thinning of Neogene deposits to the southwest due to less accommodation space.

APPENDIX FIGURE CAPTIONS

Figure A-1. Depth map (meters) of the base of the Upper North Sea Group NU (Neogene). *Inset:* same map showing all seismic lines (red) where the Base NU was interpreted and used for interpolation of the final depth map.

Figure A-2. Depth map (meters) of the *onset of folding (oof)* surface (Mid-Eocene). *Inset:* same map showing all seismic lines (red) where the *oof* surface was interpreted and used for interpolation of the final depth map.

Figure A-3. Depth map (meters) of the base of the Lower North Sea Group NL (Paleogene). *Inset:* same map showing all seismic lines (red) where the Base NL was interpreted and used for interpolation of the final depth map.

Figure A-4. Depth map (meters) of the base of the Chalk Group CK (Late Cretaceous). *Inset:* same map showing all seismic lines (red) where the Base CK was interpreted and used for interpolation of the final depth map.

Figure A-5. Depth map (meters) of the base of the Rijnland Group KN (Early Cretaceous). *Inset:* same map showing all seismic lines (red) where the Base KN was interpreted and used for interpolation of the final depth map.

Figure A-6. Thickness map (meters) of seismo-stratigraphic Unit 1 SU1 (Mid-Late Paleogene)

Figure A-7. Thickness map (meters) of seismo-stratigraphic Unit 2 SU2 (Early-Mid Paleogene)

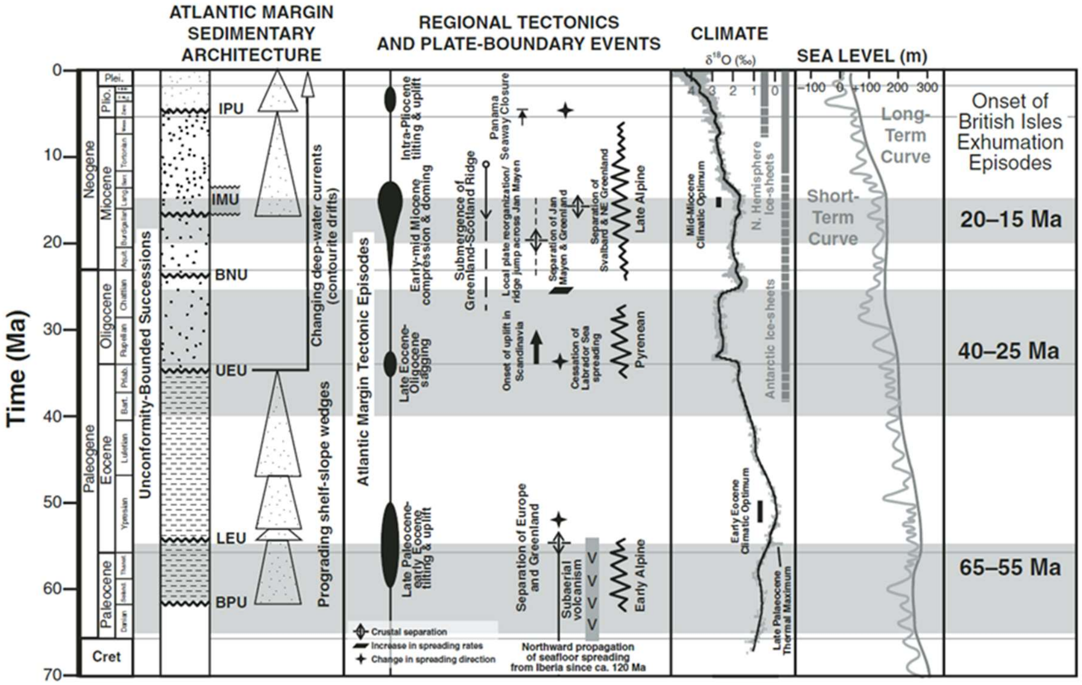
Figure A-8. Thickness map (meters) of the Chalk Group CK (Late Cretaceous)

Figure A-9. Thickness map (meters) of the Rijnland Group KN (Early Cretaceous)

Figure A-10. Horizon flattening analysis of seismic line *SNSTI-NL-87-06a.* The three profiles to the left are in time (TWT) and the three profiles to the right are in depth (km). *a* - *b.* Non-flattened seismic profiles. *c* - *d.* Flattened seismic profiles at the *oof* surface level. *e* - *f.* Flattened seismic profiles at the base Cretaceous level (KN). A dashed, white line represents the mean curve of the interpreted Base ZE. For location see Fig. 4 *a*. 7x vertical exaggeration.

FIGURES

Figure 1:



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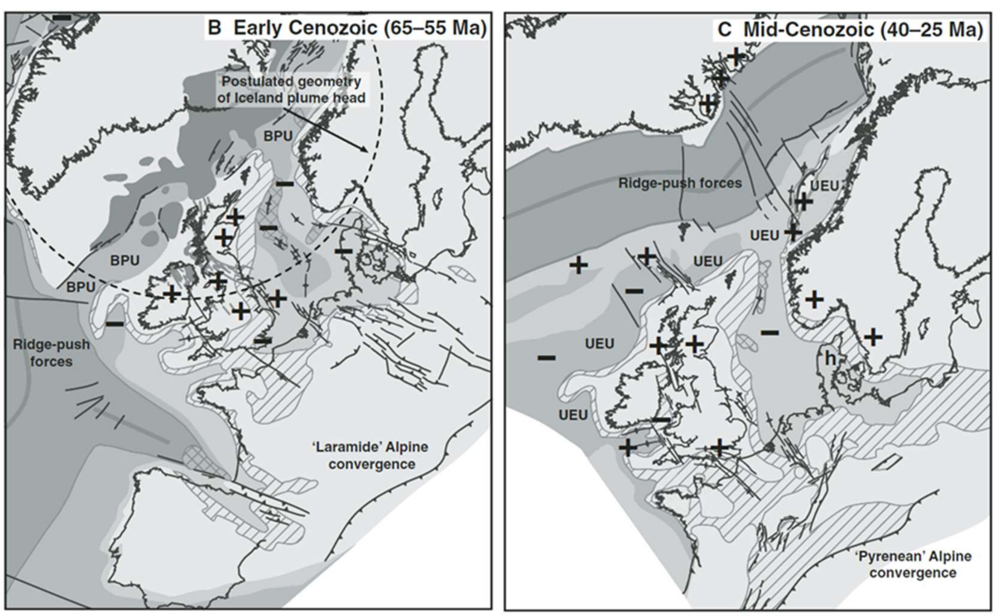

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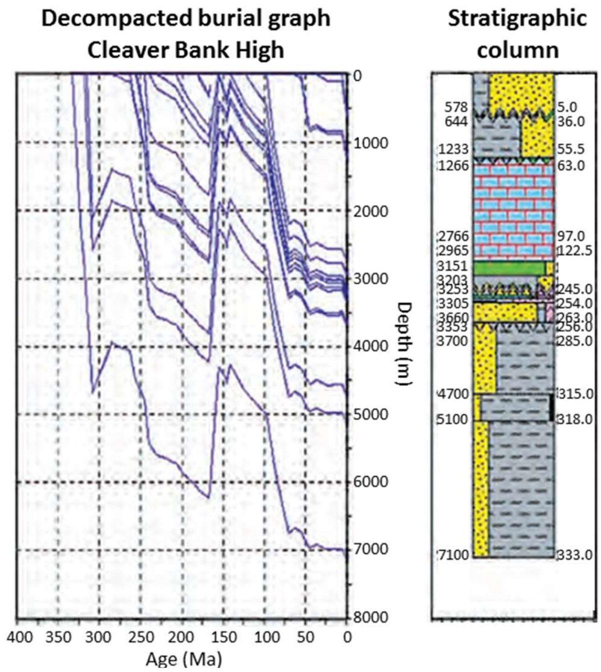

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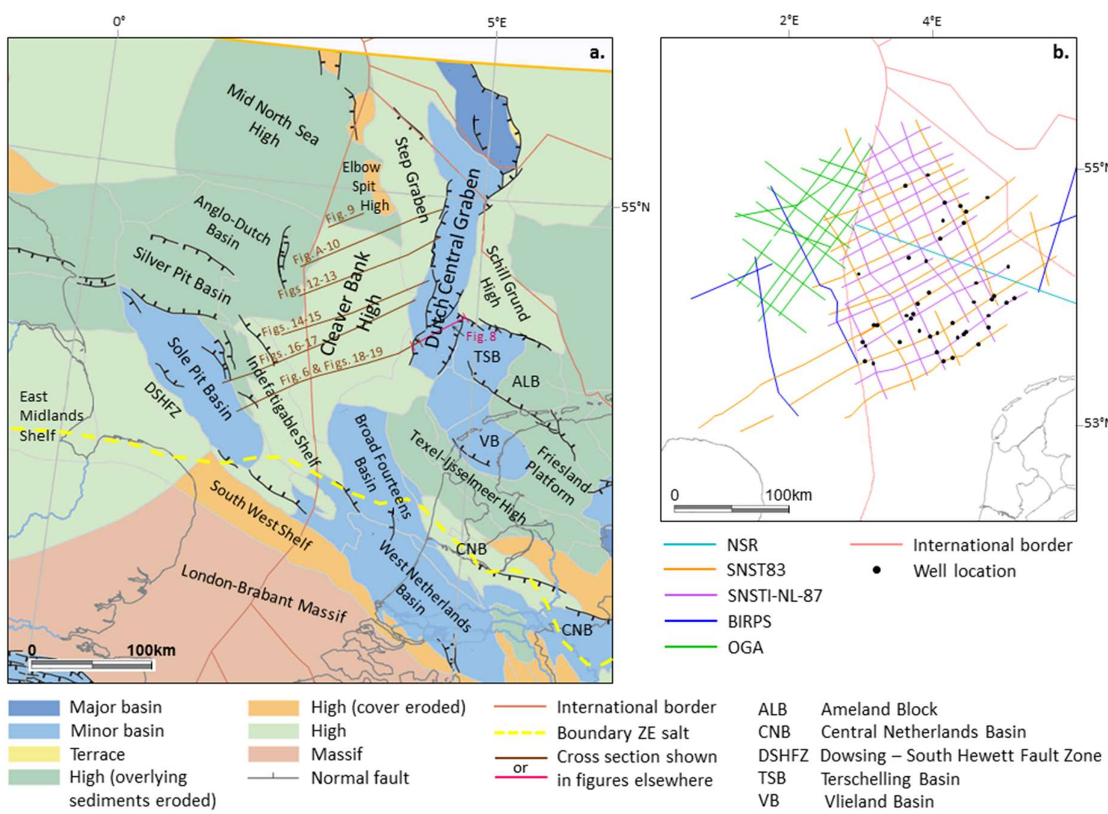

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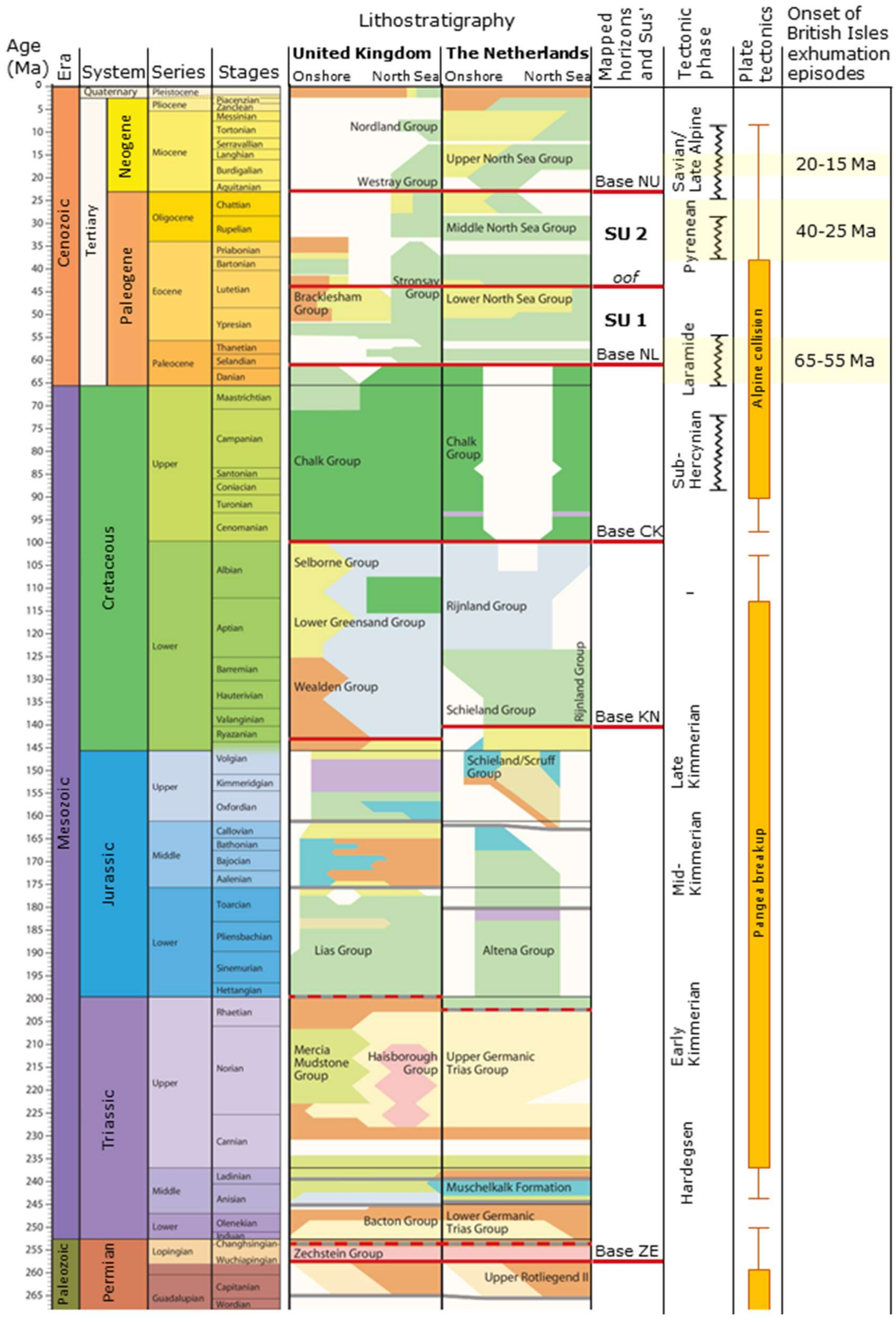


Lithostratigraphy
Age (Ma)
Era
System
Series
Stages
United Kingdom
Onshore
North Sea
The Netherlands
Onshore
North Sea
Mapped horizons and Sus'
Tectonic phase
Plate tectonics
Onset of British Isles exhumation episodes
Cenozoic
Mesozoic
Paleozoic
Quaternary
Tertiary
Neogene
Paleogene
Cretaceous
Jurassic
Triassic
Permian
Nordland Group
Westray Group
Upper North Sea Group
Middle North Sea Group
Stronsay Group
Bracklesham Group
Lower North Sea Group
Chalk Group
Selborne Group
Lower Greensand Group
Wealden Group
Rijnland Group
Schieland Group
Schieland/Scruff Group
Lias Group
Altena Group
Mercia Mudstone Group
Haisborough Group
Upper Germanic Trias Group
Muschelkalk Formation
Bacton Group
Lower Germanic Trias Group
Zechstein Group
Upper Rotliegend II
Base NU
SU 2
oof
SU 1
Base NL
Base CK
Base KN
Base ZE
Savian/ Late Alpine
Pyrenean
Laramide
Sub-Hercynian
Late Kimmerian
Mid-Kimmerian
Early Kimmerian
Hardegsen
Alpine collision
Pangea breakup
20-15 Ma
40-25 Ma
65-55 Ma

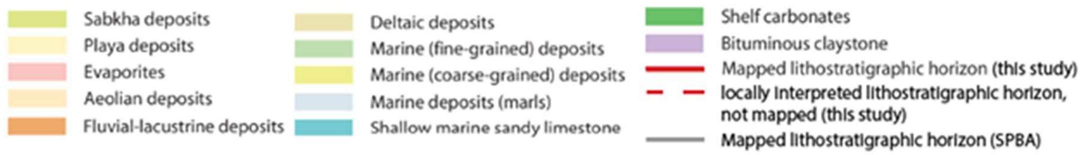
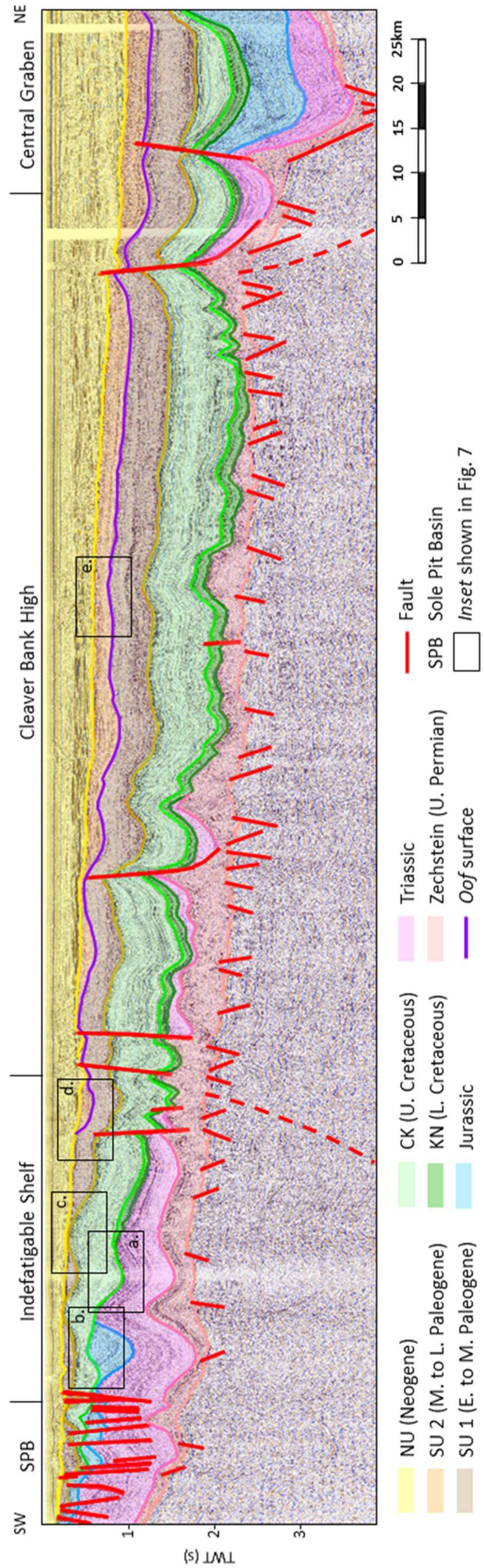

Sabkha deposits
Playa deposits
Evaporites
Aeolian deposits
Fluvial-lacustrine deposits
Deltaic deposits
Marine (fine-grained) deposits
Marine (coarse-grained) deposits
Marine deposits (marls)
Shallow marine sandy limestone
Shelf carbonates
Bituminous claystone
Mapped lithostratigraphic horizon (this study)
locally interpreted lithostratigraphic horizon, not mapped (this study)
Mapped lithostratigraphic horizon (SPBA)

Figure 6:



SW
NE
SPB
Indefatigable Shelf
Cleaver Bank High
Central Graben
TWT (s)
1
2
3
a.
b.
c.
d.
e.
0
5
10
15
20
25km
NU (Neogene)
SU 2 (M. to L. Paleogene)
SU 1 (E. to M. Paleogene)
CK (U. Cretaceous)
KN (L. Cretaceous)
Jurassic
Triassic
Zechstein (U. Permian)
Oof surface
Fault
SPB Sole Pit Basin
Inset shown in Fig. 7

Figure 7:

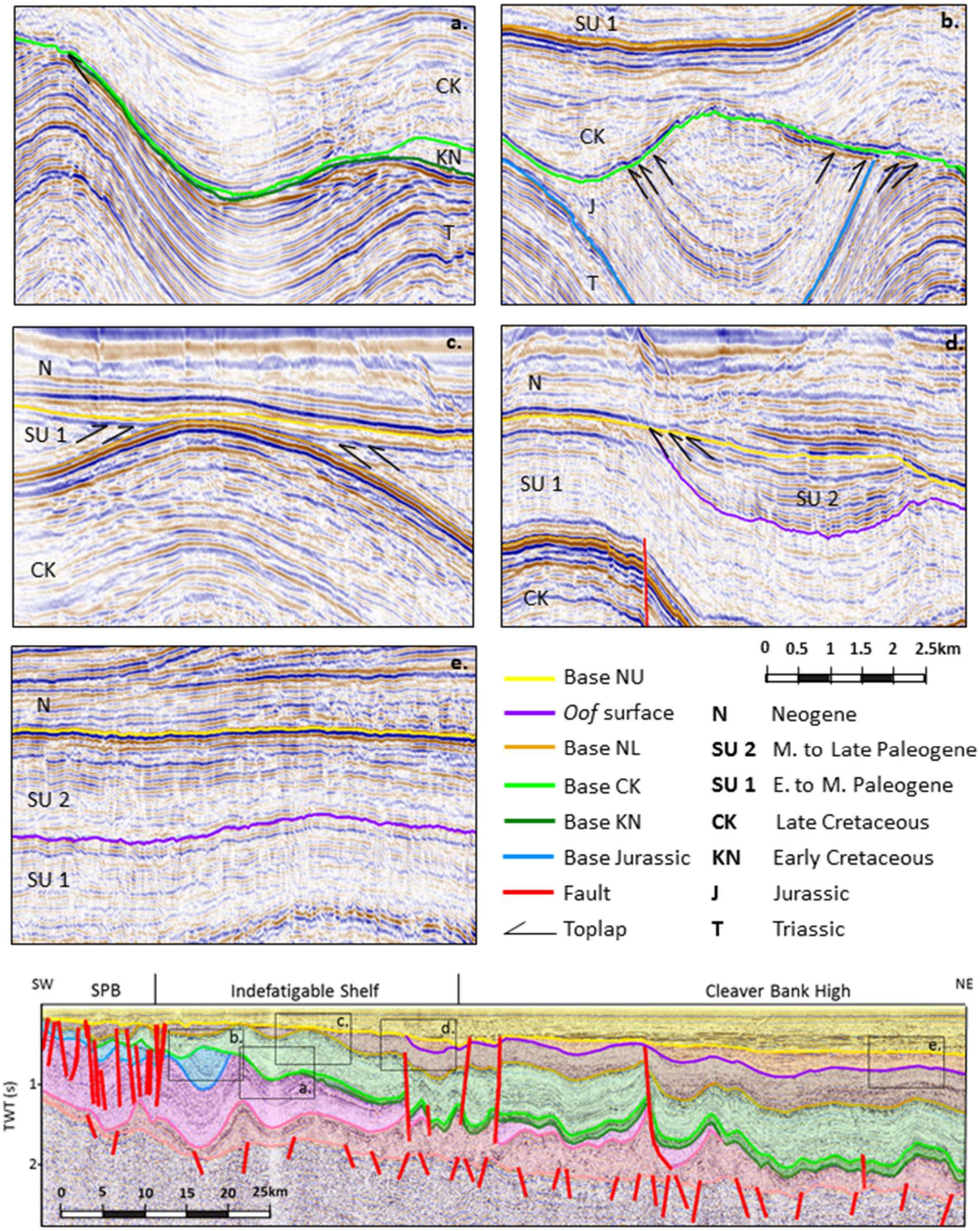
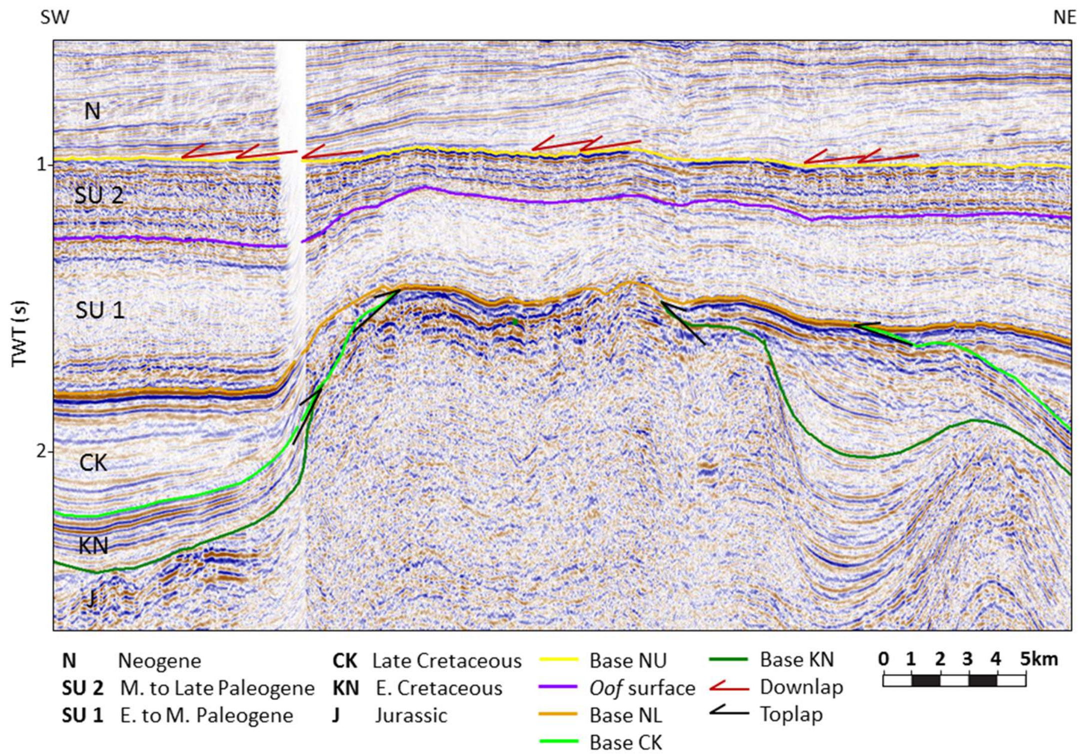

a.
CK
KN
T
b.
SU 1
CK
J
T
c.
N
SU 1
CK
d.
N
SU 1
SU 2
CK
e.
N
SU 2
SU 1
0 0.5 1 1.5 2 2.5km
Base NU
Oof surface
Base NL
Base CK
Base KN
Base Jurassic
Fault
Toplap
N Neogene
SU 2 M. to Late Paleogene
SU 1 E. to M. Paleogene
CK Late Cretaceous
KN Early Cretaceous
J Jurassic
T Triassic
SW
SPB
Indefatigable Shelf
Cleaver Bank High
NE
TWT (s)
1
2
0 5 10 15 20 25km

Figure 8:



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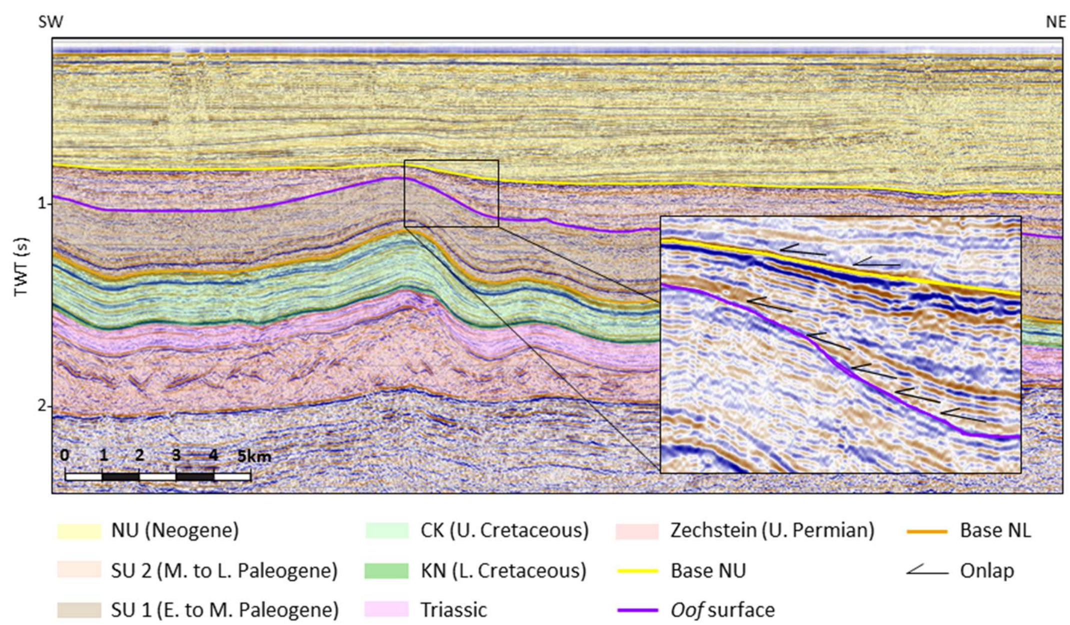

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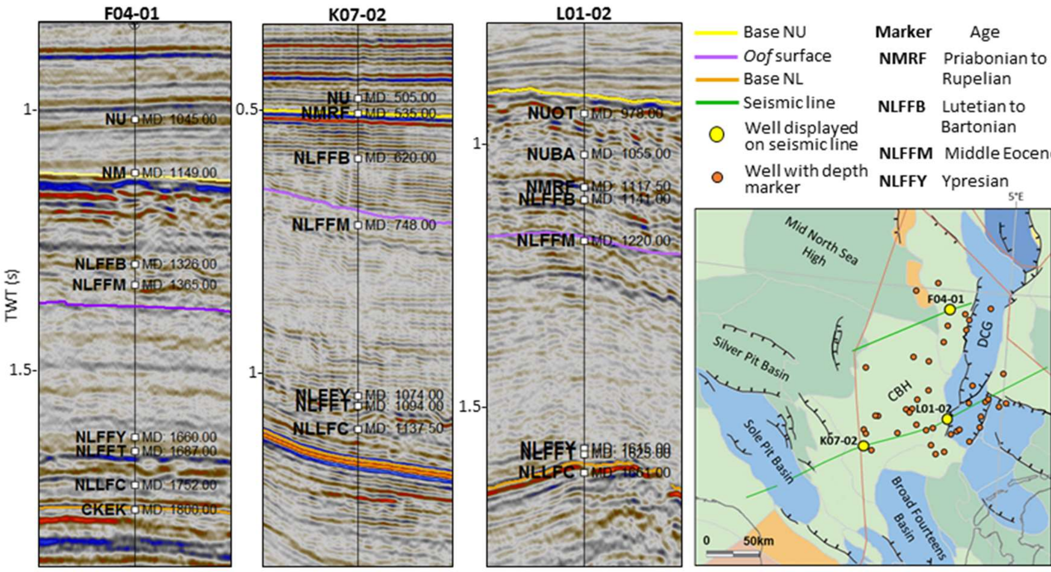

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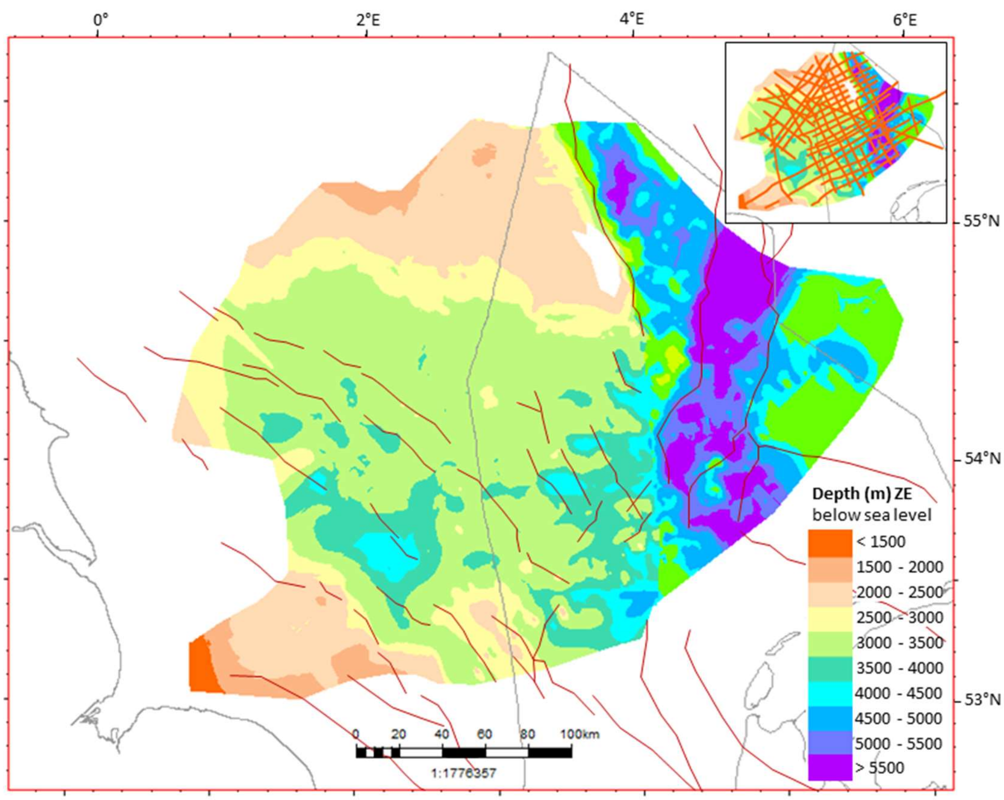

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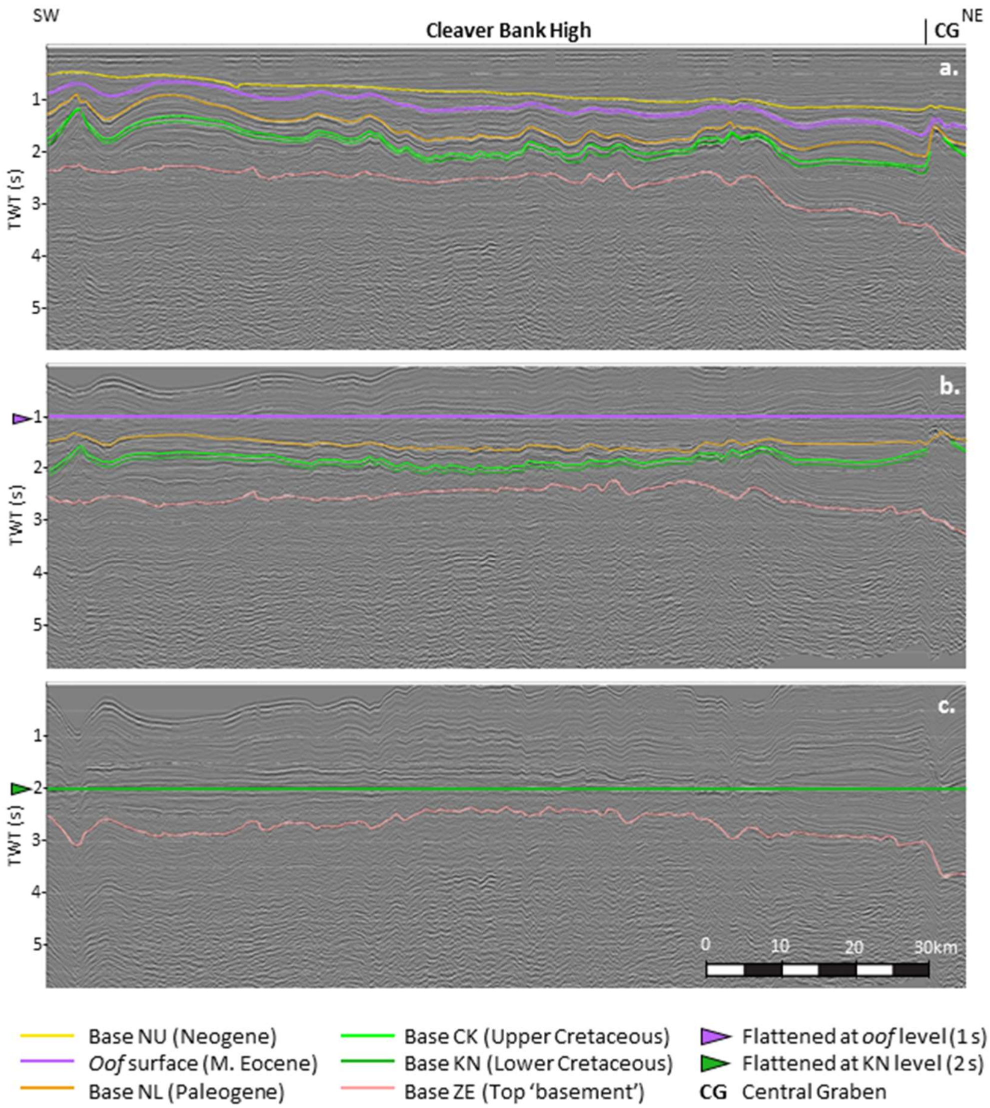

SW
Cleaver Bank High
CG
NE
a.
b.
c.
TWT (s)
1
2
3
4
5
0
10
20
30km
Base NU (Neogene)
Oof surface (M. Eocene)
Base NL (Paleogene)
Base CK (Upper Cretaceous)
Base KN (Lower Cretaceous)
Base ZE (Top 'basement')
Flattened at oof level (1 s)
Flattened at KN level (2 s)
CG Central Graben

Figure 13:

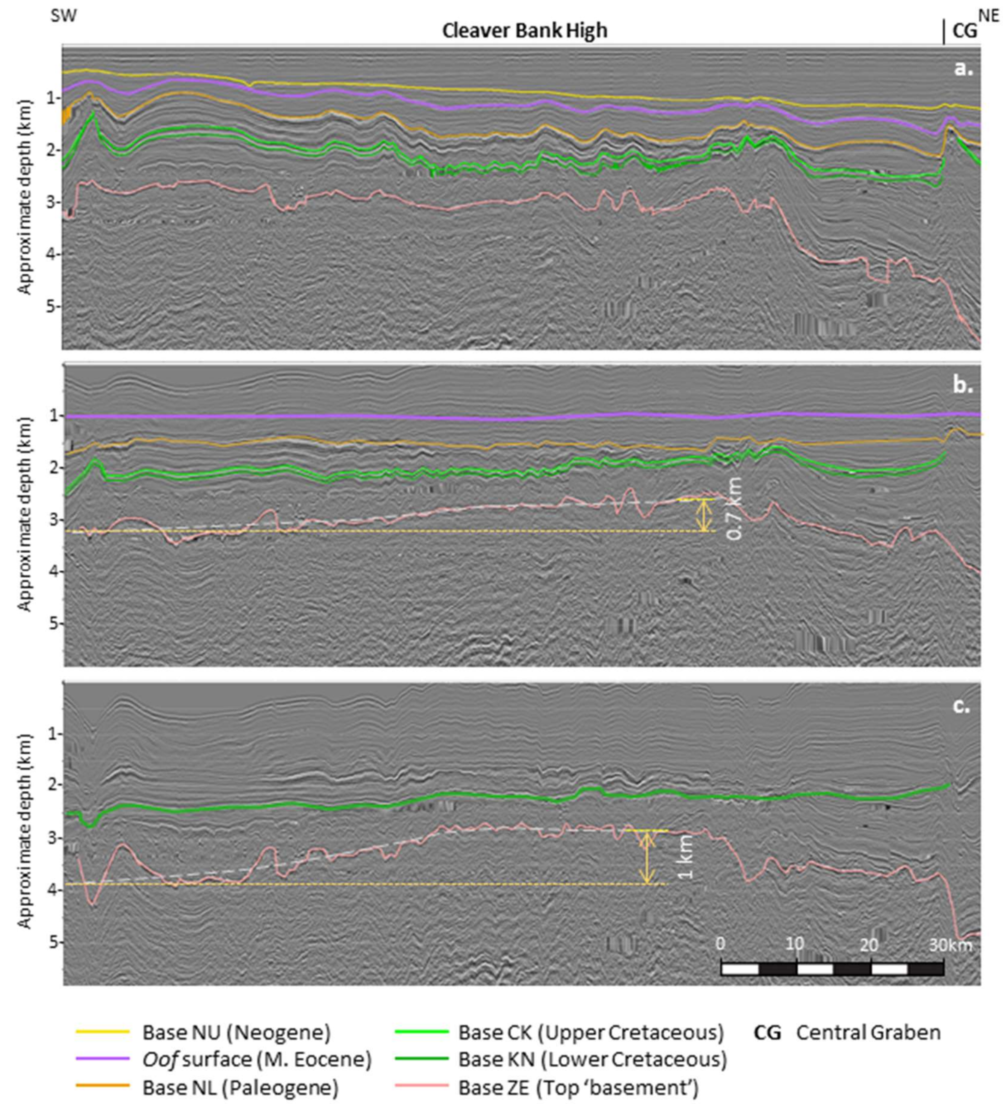
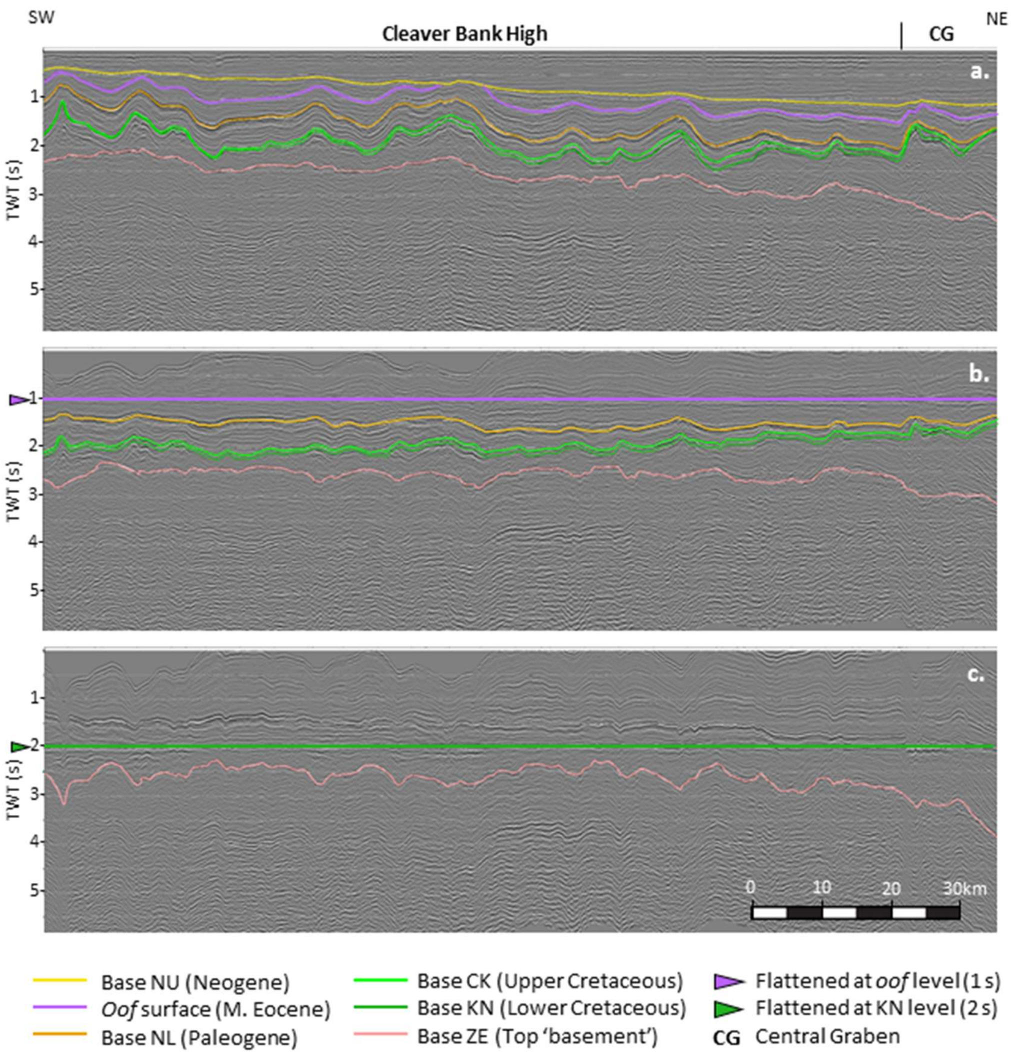

SW
Cleaver Bank High
CG
NE
a.
b.
c.
Approximate depth (km)
0.7 km
1 km
0
10
20
30km
Base NU (Neogene)
Oof surface (M. Eocene)
Base NL (Paleogene)
Base CK (Upper Cretaceous)
Base KN (Lower Cretaceous)
Base ZE (Top 'basement')
CG Central Graben

Figure 14:



SW
Cleaver Bank High
CG
NE
a.
b.
c.
TWT (s)
TWT (s)
TWT (s)
0
10
20
30km
Base NU (Neogene)
Oof surface (M. Eocene)
Base NL (Paleogene)
Base CK (Upper Cretaceous)
Base KN (Lower Cretaceous)
Base ZE (Top 'basement')
Flattened at *oof* level (1 s)
Flattened at KN level (2 s)
CG Central Graben

Figure 15:

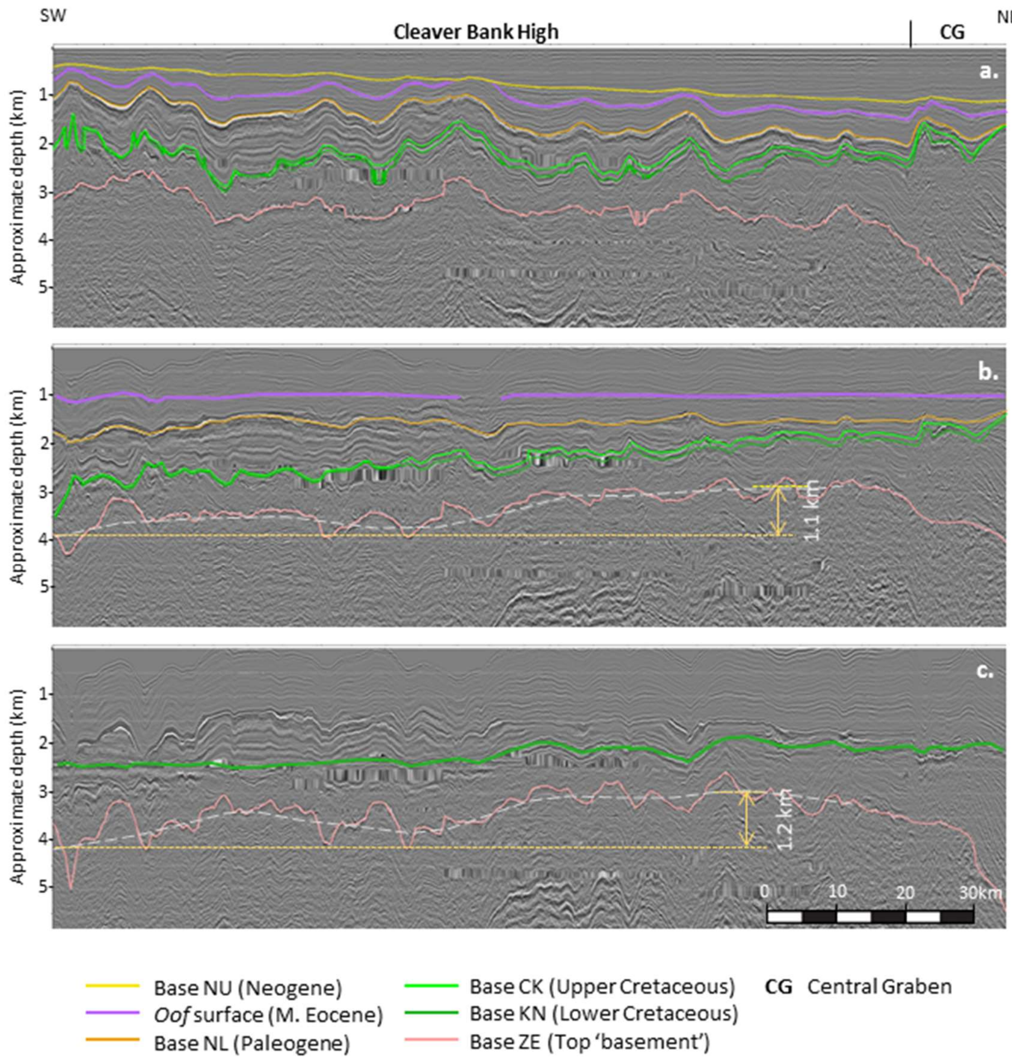
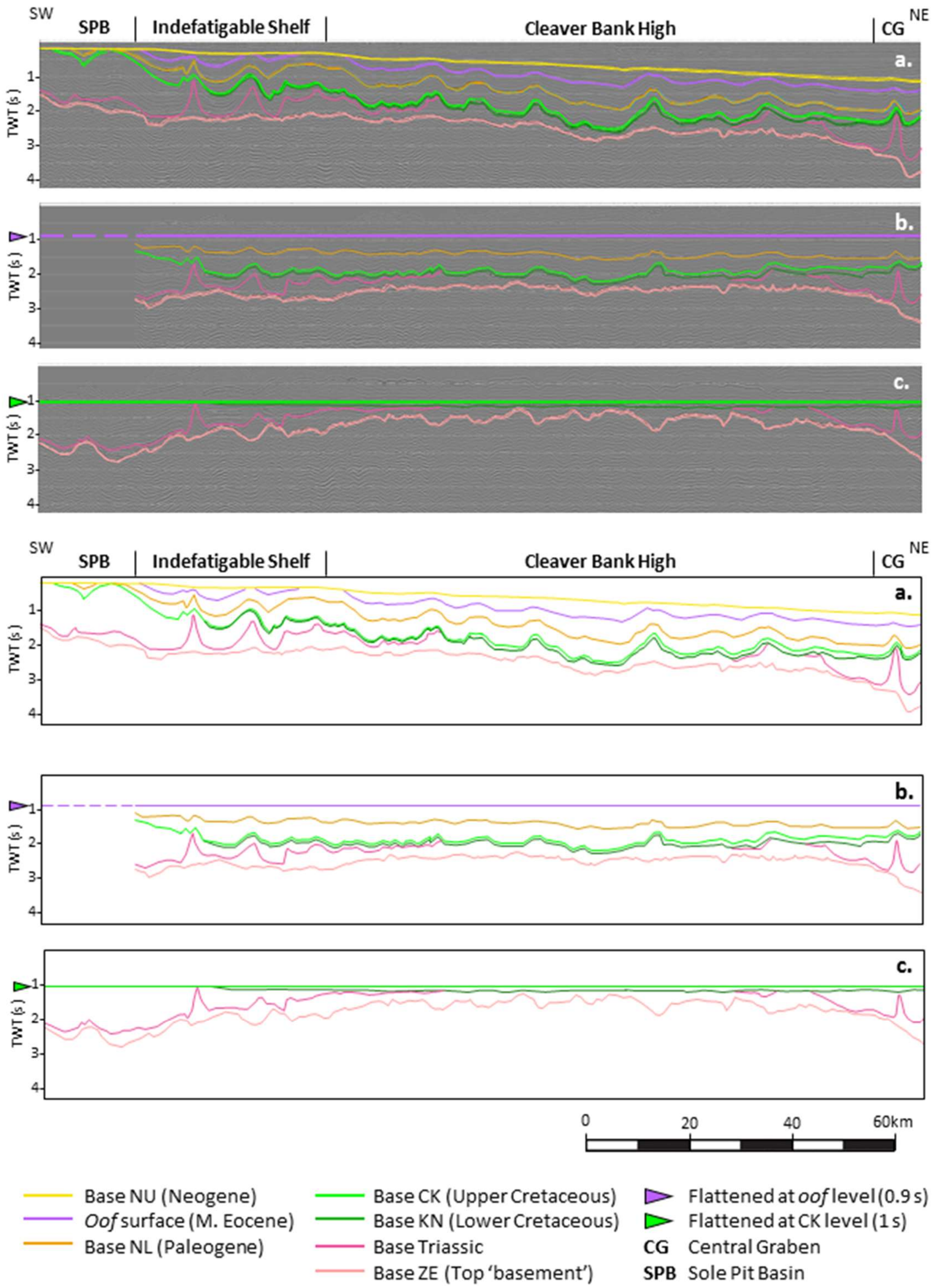
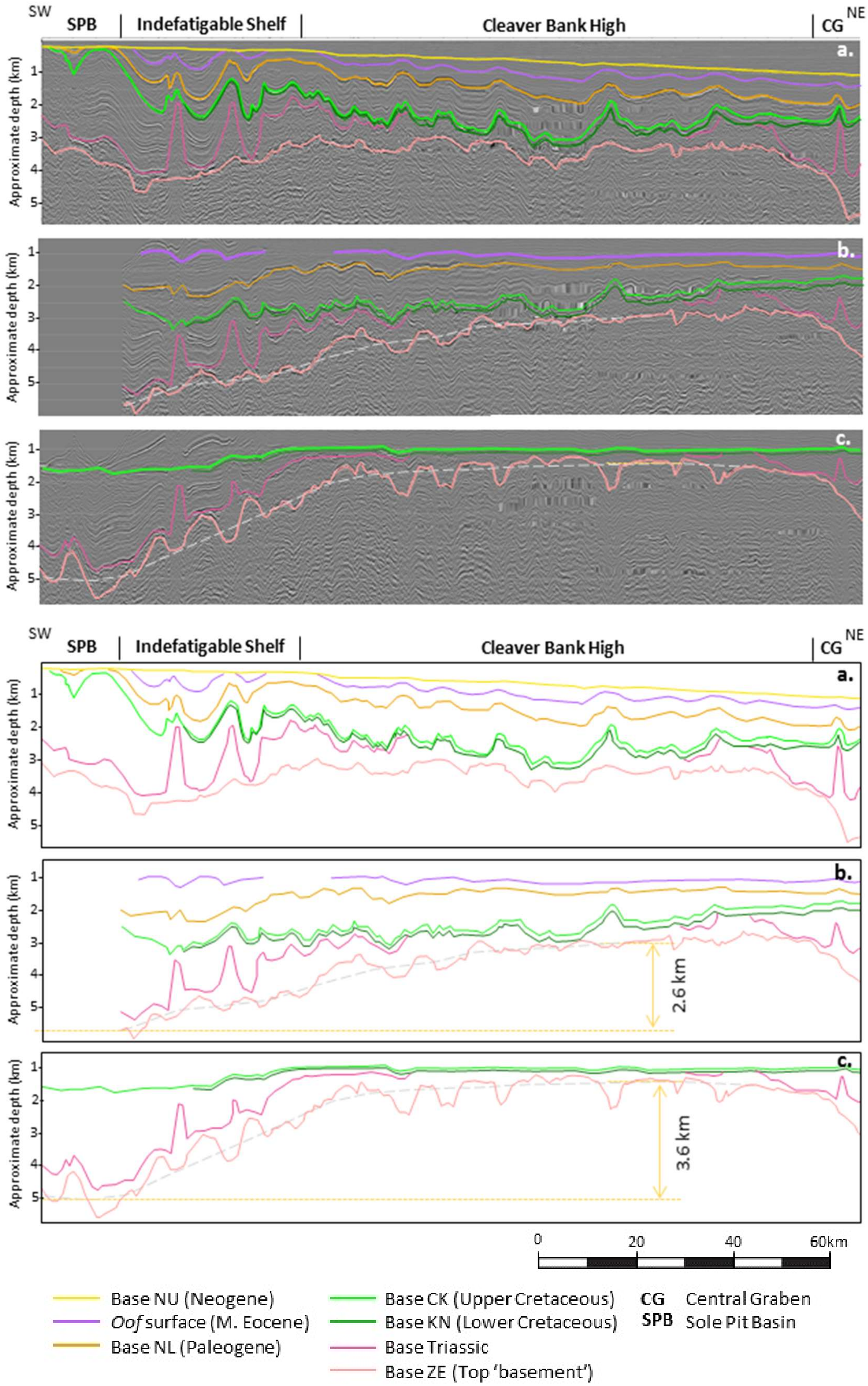

SW
Cleaver Bank High
CG
NE
a.
b.
c.
Approximate depth (km)
1
2
3
4
5
1.1 km
1.2 km
0
10
20
30km
Base NU (Neogene)
Oof surface (M. Eocene)
Base NL (Paleogene)
Base CK (Upper Cretaceous)
Base KN (Lower Cretaceous)
Base ZE (Top 'basement')
CG Central Graben

Figure 16:



SW
SPB
Indefatigable Shelf
Cleaver Bank High
CG
NE
a.
b.
c.
TWT (s)
1
2
3
4
0
20
40
60km
Base NU (Neogene)
Oof surface (M. Eocene)
Base NL (Paleogene)
Base CK (Upper Cretaceous)
Base KN (Lower Cretaceous)
Base Triassic
Base ZE (Top 'basement')
Flattened at *oof* level (0.9 s)
Flattened at CK level (1 s)
CG Central Graben
SPB Sole Pit Basin

Figure 17:



SW
SPB
Indefatigable Shelf
Cleaver Bank High
CG
NE
a.
b.
c.
Approximate depth (km)
1
2
3
4
5
SW
SPB
Indefatigable Shelf
Cleaver Bank High
CG
NE
a.
b.
2.6 km
c.
3.6 km
Approximate depth (km)
0
20
40
60km
Base NU (Neogene)
Oof surface (M. Eocene)
Base NL (Paleogene)
Base CK (Upper Cretaceous)
Base KN (Lower Cretaceous)
Base Triassic
Base ZE (Top 'basement')
CG Central Graben
SPB Sole Pit Basin

Figure 18:

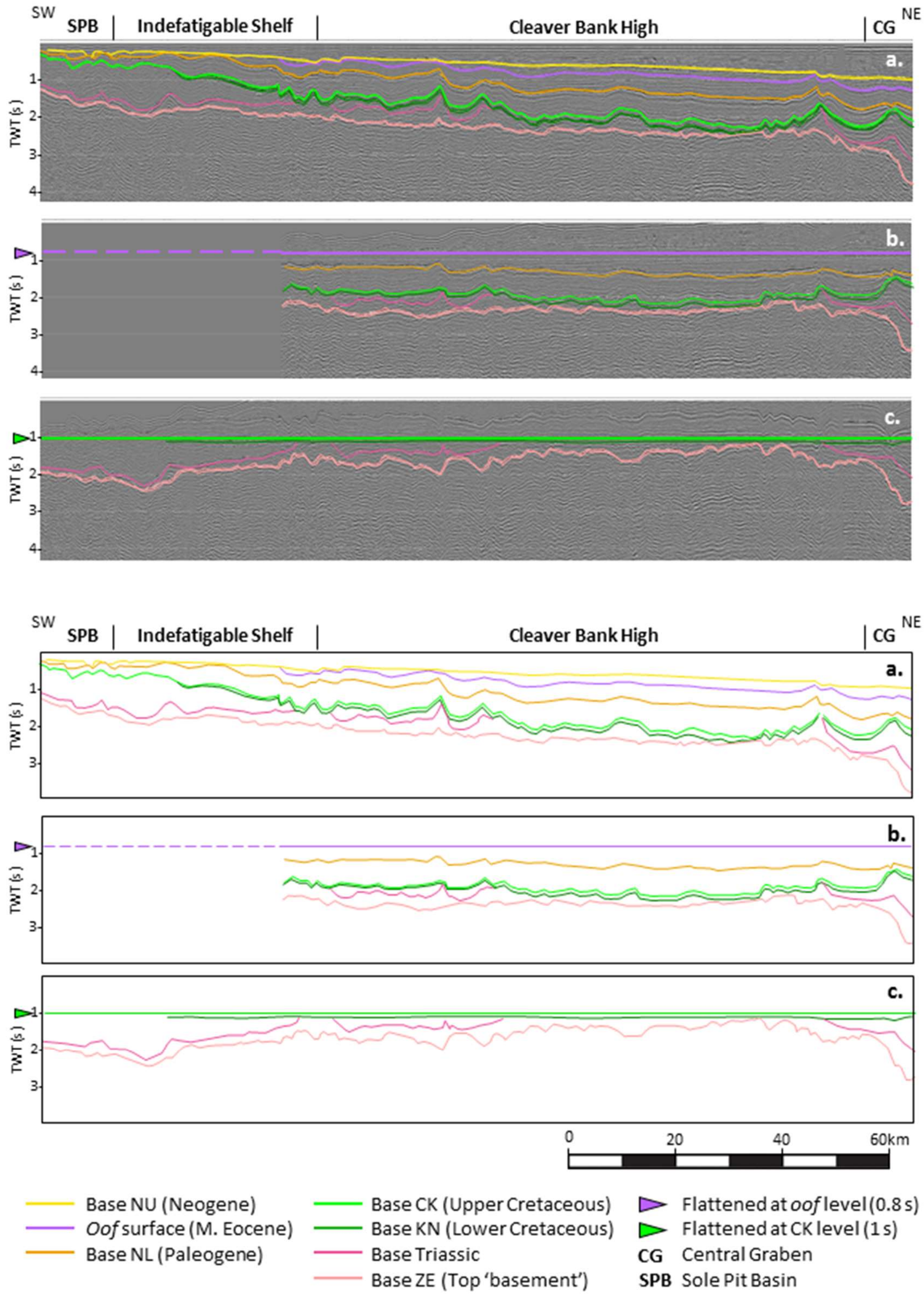

SW
SPB
Indefatigable Shelf
Cleaver Bank High
CG
NE
a.
b.
c.
TWT (s)
1
2
3
4
0
20
40
60km
Base NU (Neogene)
Oof surface (M. Eocene)
Base NL (Paleogene)
Base CK (Upper Cretaceous)
Base KN (Lower Cretaceous)
Base Triassic
Base ZE (Top 'basement')
Flattened at oof level (0.8 s)
Flattened at CK level (1 s)
CG Central Graben
SPB Sole Pit Basin

Figure 19:

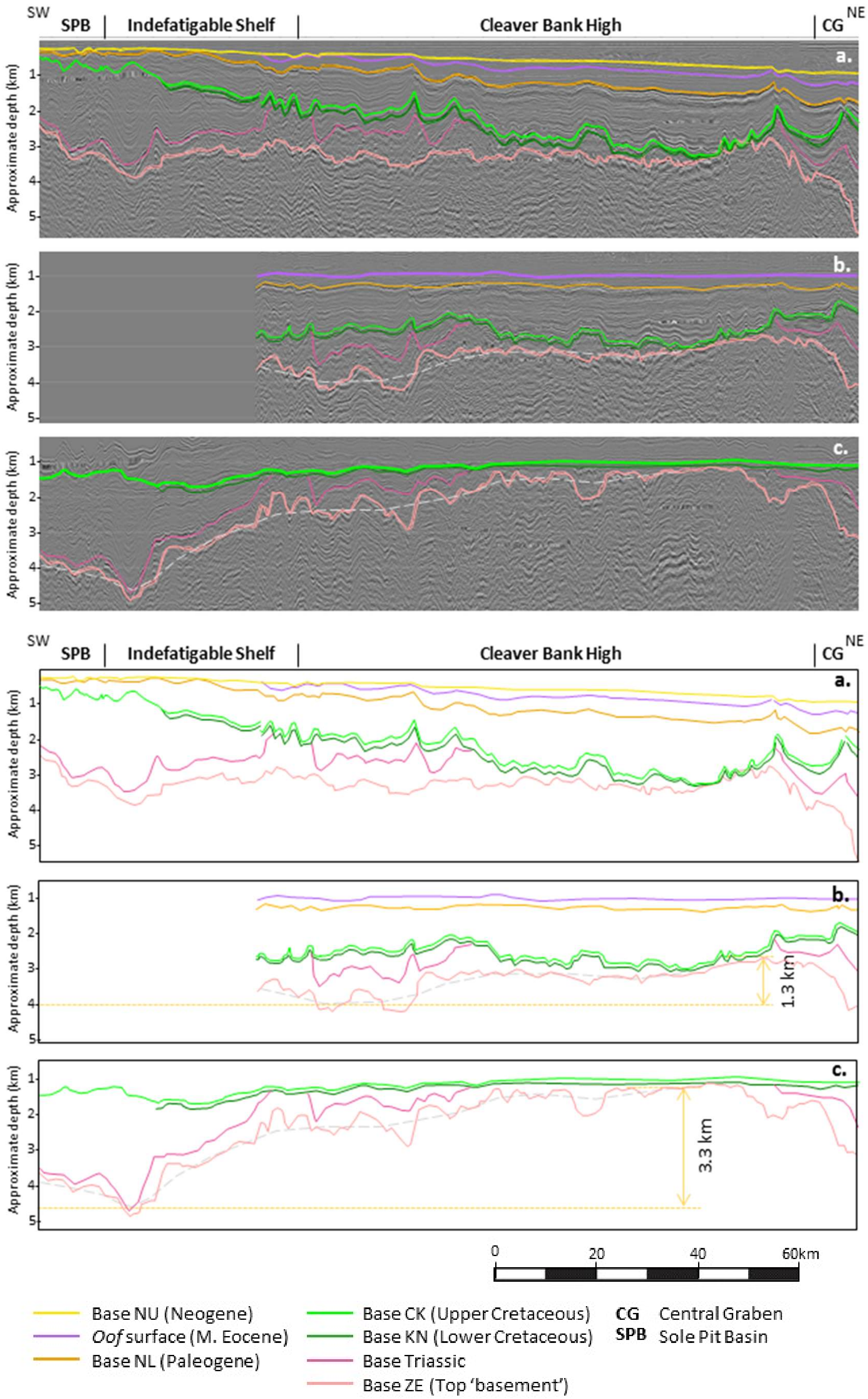

SW
SPB
Indefatigable Shelf
Cleaver Bank High
CG
NE
a.
b.
c.
Approximate depth (km)
1.3 km
3.3 km
0
20
40
60km
Base NU (Neogene)
Oof surface (M. Eocene)
Base NL (Paleogene)
Base CK (Upper Cretaceous)
Base KN (Lower Cretaceous)
Base Triassic
Base ZE (Top 'basement')
CG Central Graben
SPB Sole Pit Basin

Figure 20:

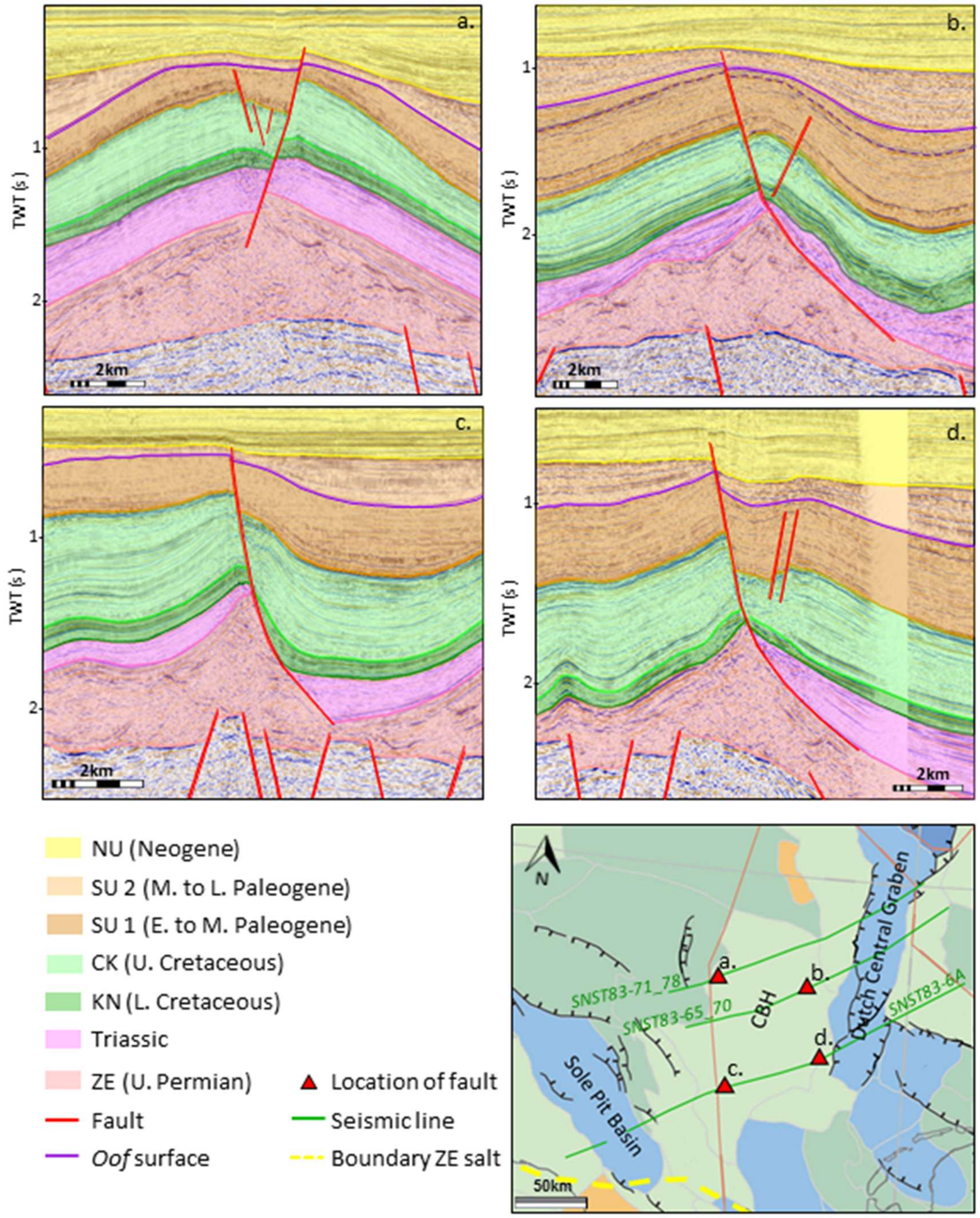

a.
b.
c.
d.
TWT (s)
1
2
2km
NU (Neogene)
SU 2 (M. to L. Paleogene)
SU 1 (E. to M. Paleogene)
CK (U. Cretaceous)
KN (L. Cretaceous)
Triassic
ZE (U. Permian)
Fault
Oof surface
Location of fault
Seismic line
Boundary ZE salt
N
SNST83-71_78
SNST83-65_70
SNST83-6A
CBH
Dutch Central Graben
Sole Pit Basin
50km

Figure 21:

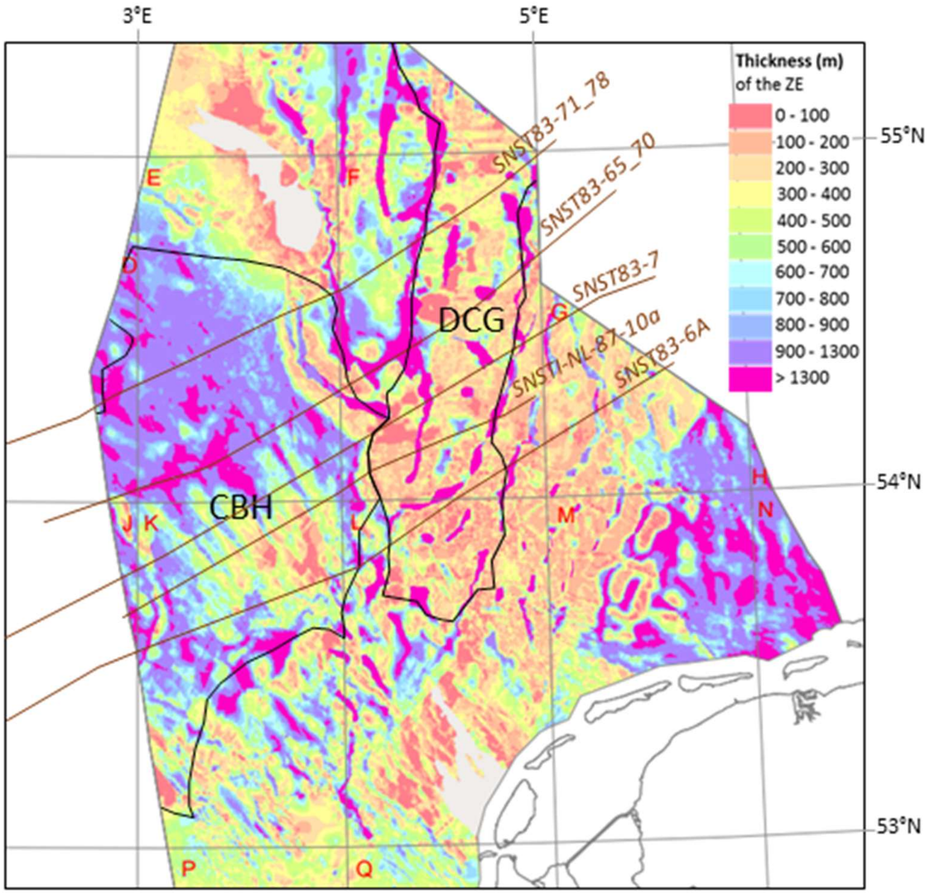
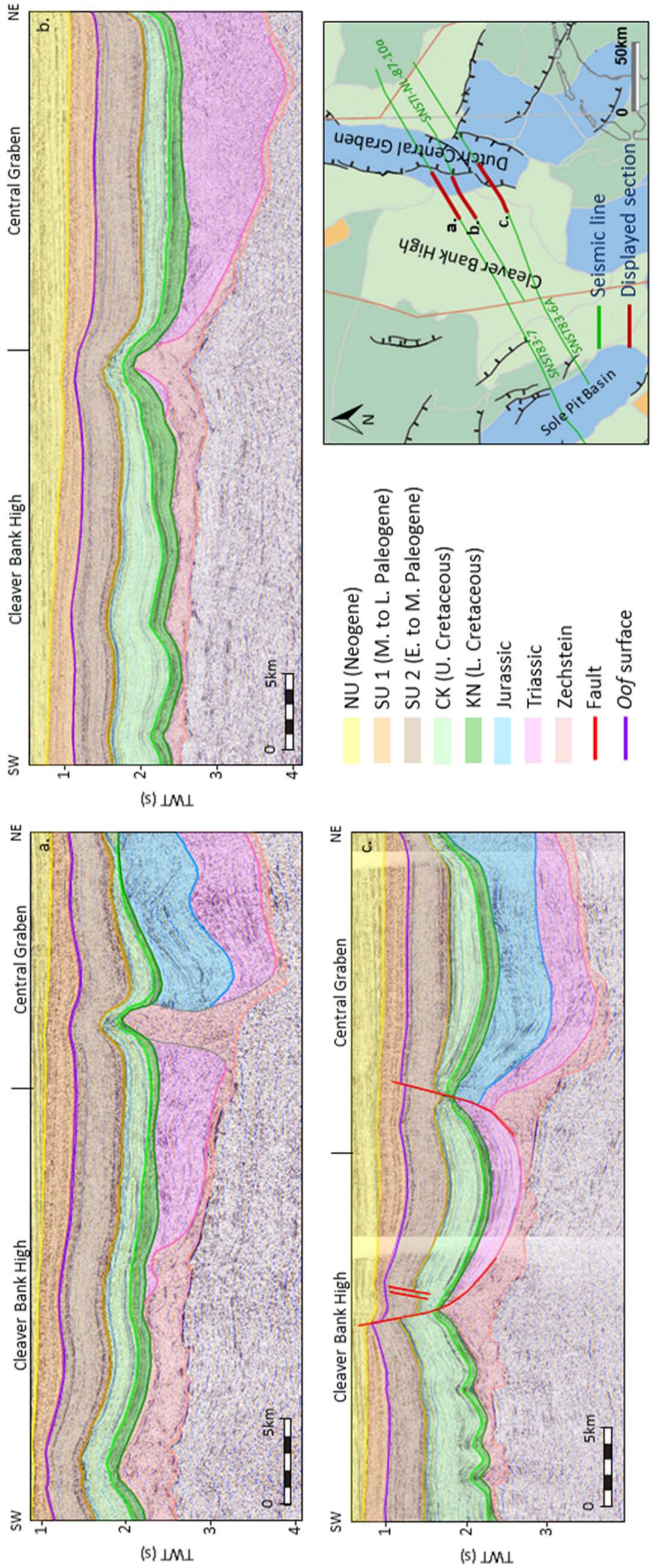
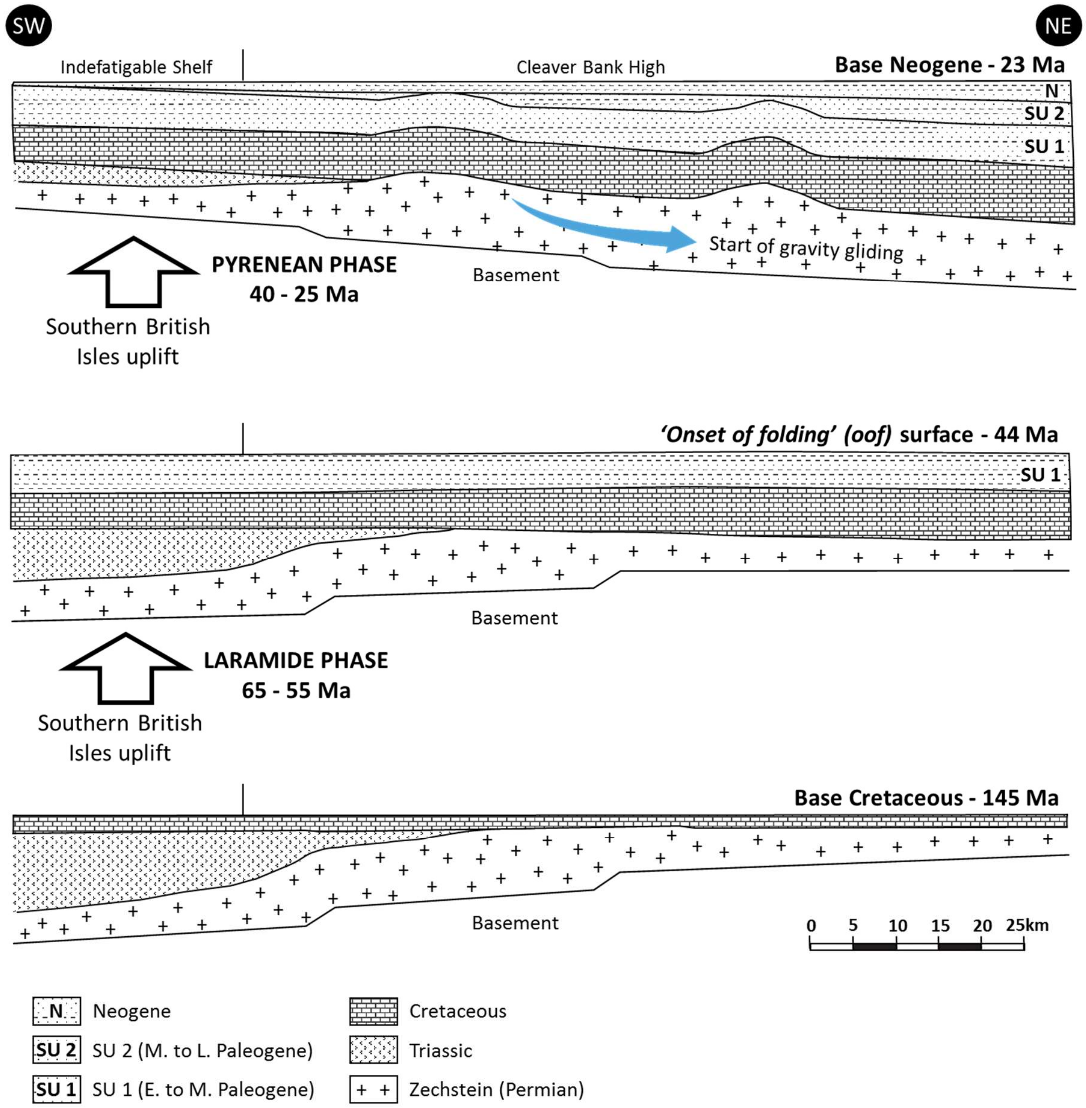

3°E
5°E
55°N
54°N
53°N
Thickness (m)
of the ZE
0 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
700 - 800
800 - 900
900 - 1300
> 1300
SNST83-71_78
SNST83-65_70
SNST83-7
SNSTI-NL-87-10a
SNST83-6A
DCG
CBH
E
F
D
G
H
J
K
L
M
N
P
Q

Figure 22:



SW
NE
Central Graben
Cleaver Bank High
TWT (s)
5km
a.
b.
c.
NU (Neogene)
SU 1 (M. to L. Paleogene)
SU 2 (E. to M. Paleogene)
CK (U. Cretaceous)
KN (L. Cretaceous)
Jurassic
Triassic
Zechstein
Fault
Oof surface
Dutch Central Graben
Cleaver Bank High
Sole Pit Basin
Seismic line
Displayed section
50km

Figure 23:


SW
NE
Indefatigable Shelf
Cleaver Bank High
Base Neogene - 23 Ma
N
SU 2
SU 1
Start of gravity gliding
PYRENEAN PHASE
40 - 25 Ma
Basement
Southern British
Isles uplift
'Onset of folding' (oof) surface - 44 Ma
SU 1
Basement
LARAMIDE PHASE
65 - 55 Ma
Southern British
Isles uplift
Base Cretaceous - 145 Ma
Basement
0 5 10 15 20 25km
N Neogene
SU 2 SU 2 (M. to L. Paleogene)
SU 1 SU 1 (E. to M. Paleogene)
Cretaceous
Triassic
+ + Zechstein (Permian)

APPENDIX

Figure A-1:

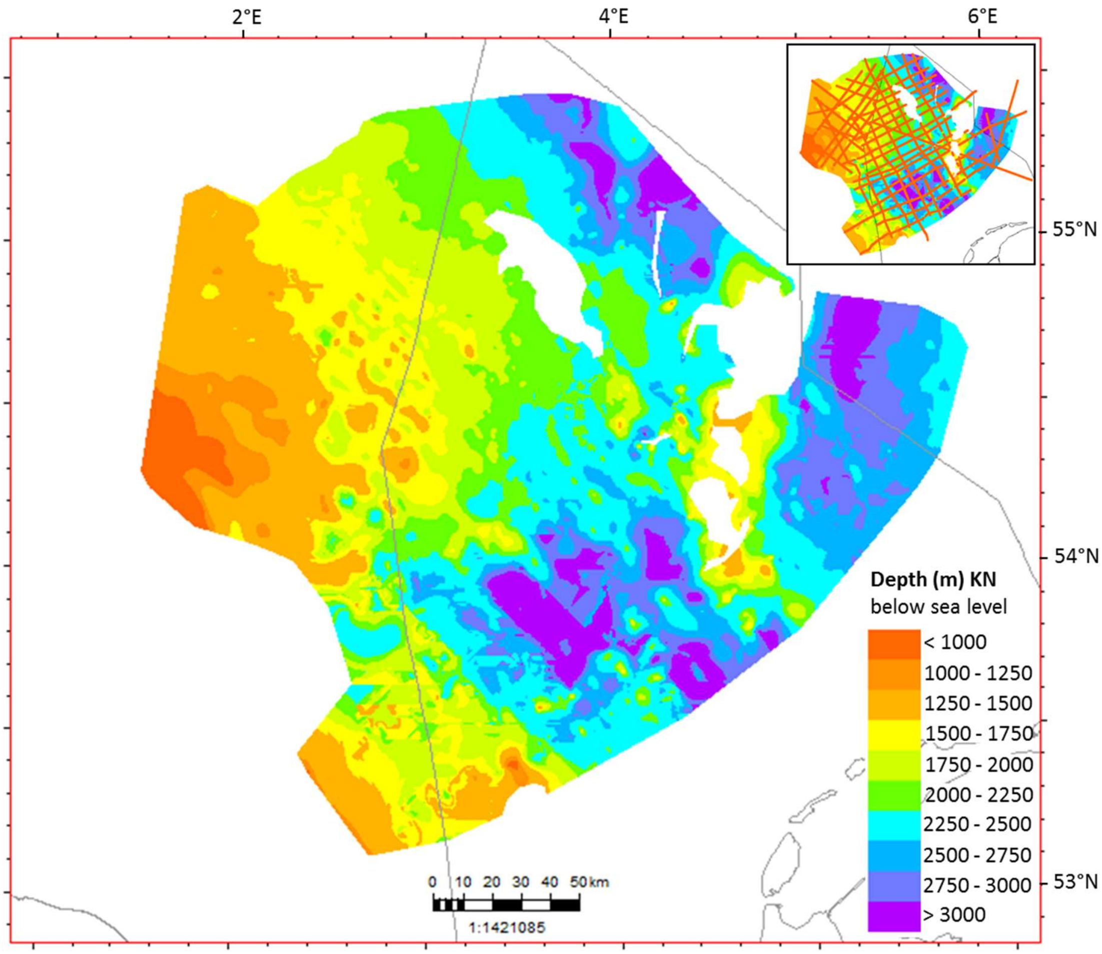


Figure A-2:

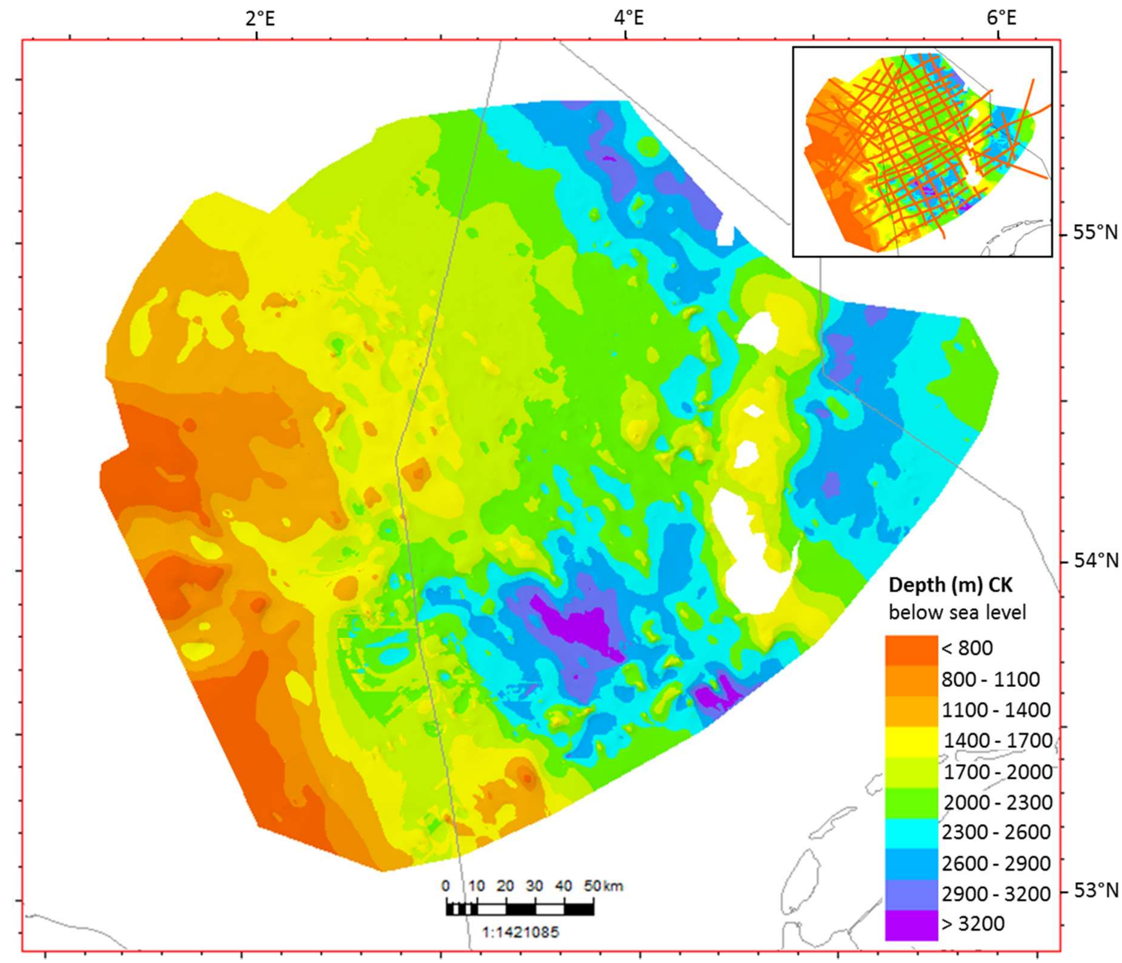

2°E
4°E
6°E
55°N
54°N
53°N
0 10 20 30 40 50 km
1:1421085
Depth (m) CK
below sea level
< 800
800 - 1100
1100 - 1400
1400 - 1700
1700 - 2000
2000 - 2300
2300 - 2600
2600 - 2900
2900 - 3200
> 3200

Figure A-3:

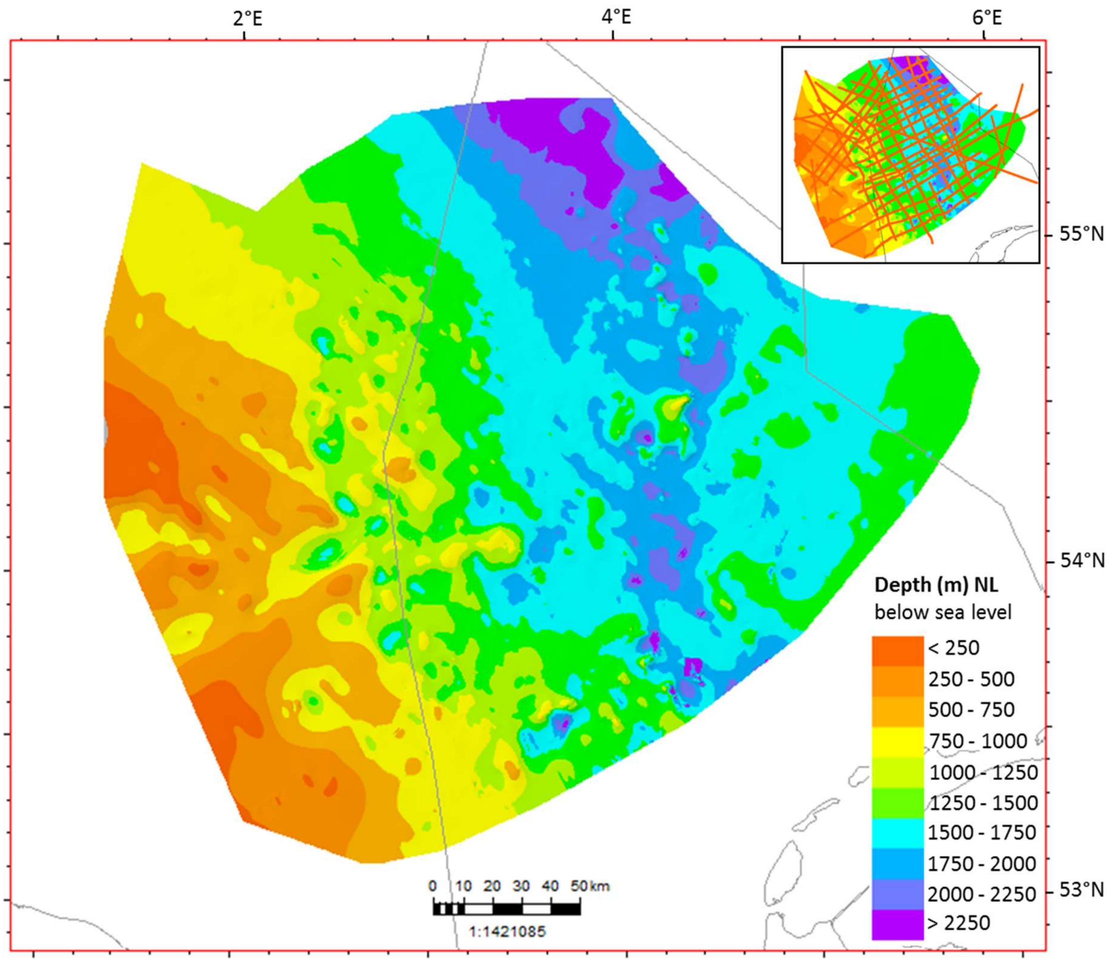

2°E
4°E
6°E
55°N
54°N
53°N
Depth (m) NL
below sea level
< 250
250 - 500
500 - 750
750 - 1000
1000 - 1250
1250 - 1500
1500 - 1750
1750 - 2000
2000 - 2250
> 2250
0 10 20 30 40 50 km
1:1421085

Figure A-4:

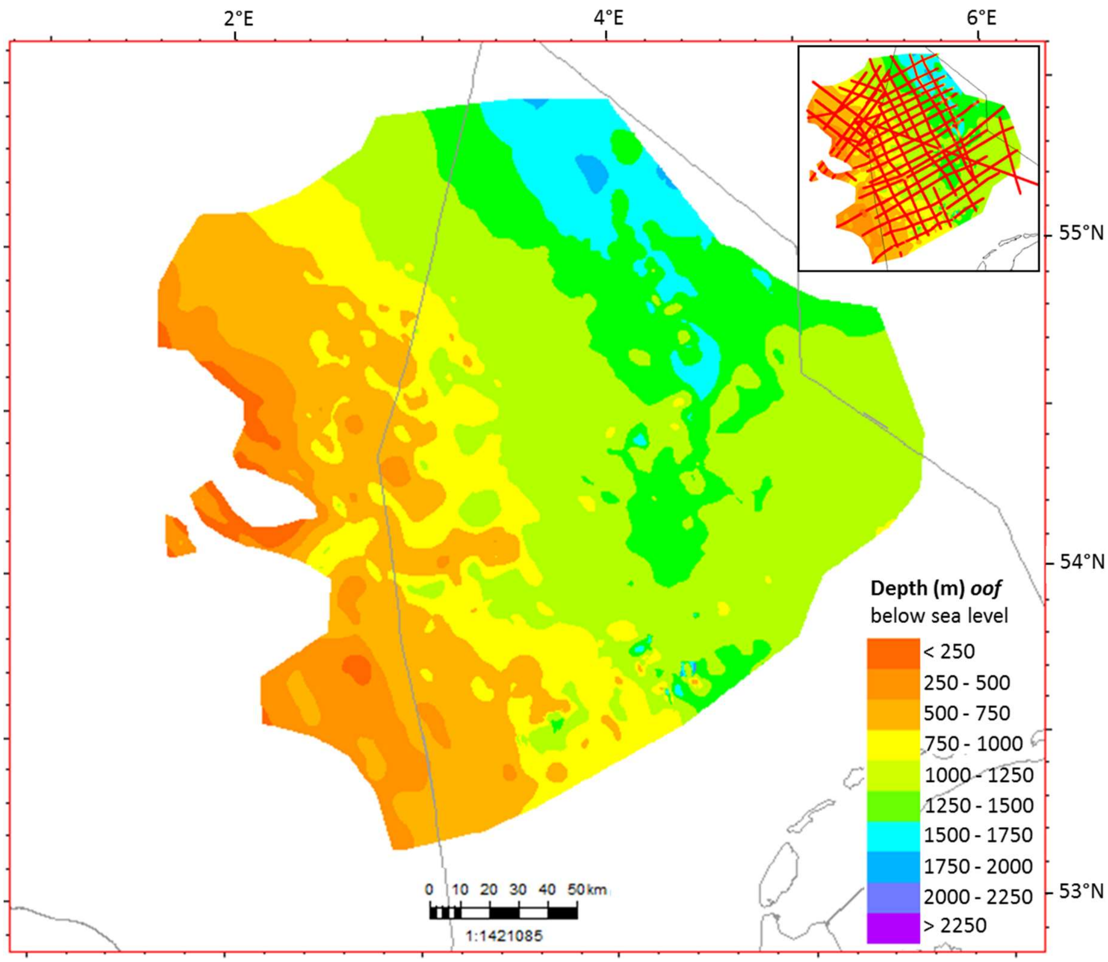

2°E
4°E
6°E
55°N
54°N
53°N
Depth (m) *oof*
below sea level
< 250
250 - 500
500 - 750
750 - 1000
1000 - 1250
1250 - 1500
1500 - 1750
1750 - 2000
2000 - 2250
> 2250
0 10 20 30 40 50 km
1:1421085

Figure A-5:

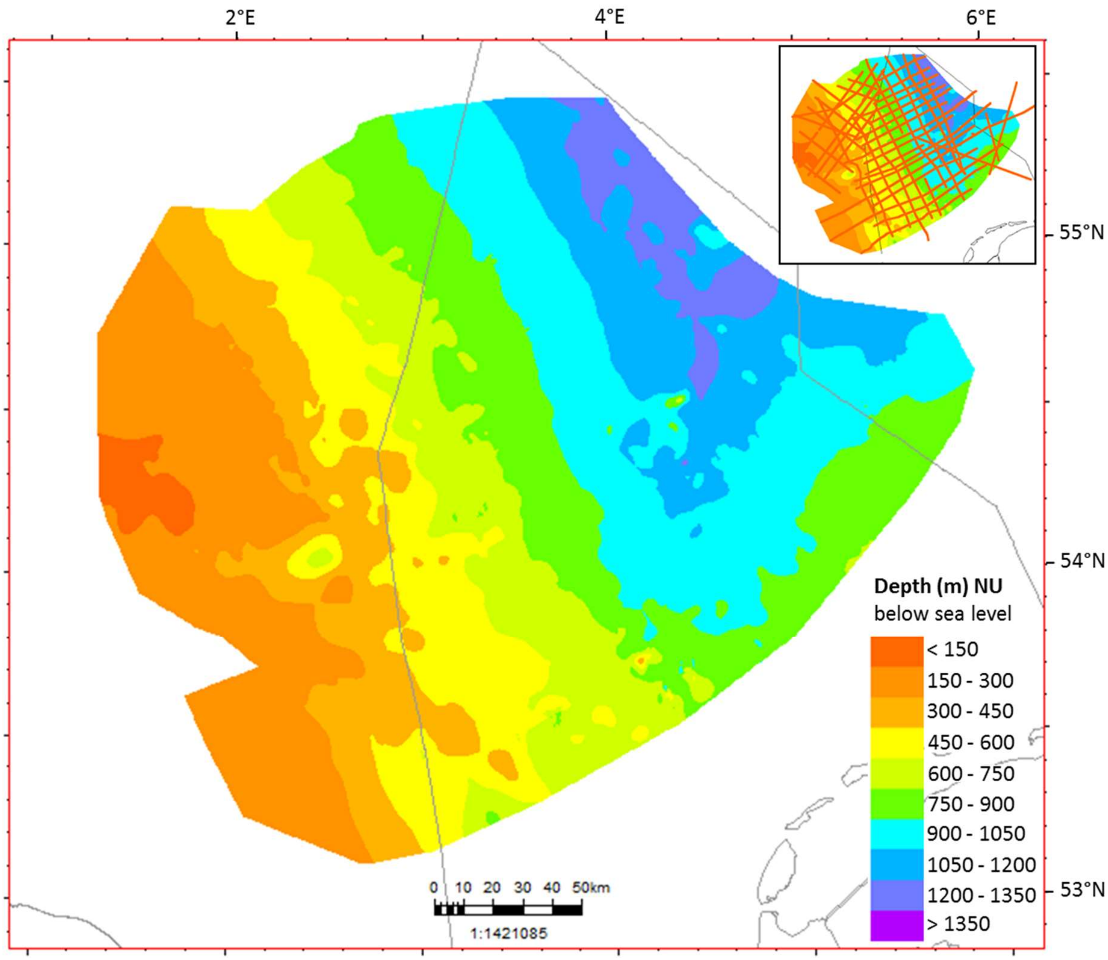
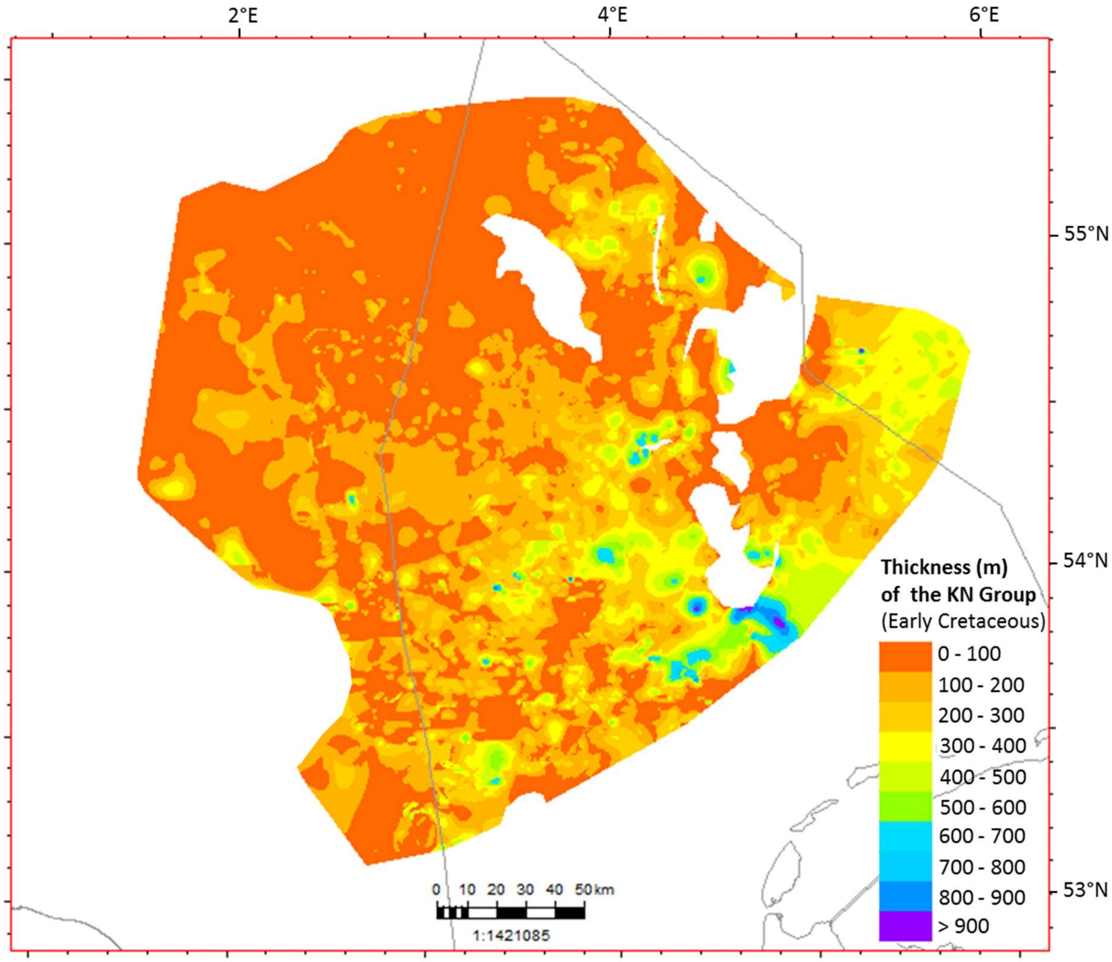

2°E
4°E
6°E
55°N
54°N
53°N
0 10 20 30 40 50km
1:1421085
Depth (m) NU
below sea level
< 150
150 - 300
300 - 450
450 - 600
600 - 750
750 - 900
900 - 1050
1050 - 1200
1200 - 1350
> 1350

Figure A-6:



2°E
4°E
6°E
55°N
54°N
53°N
Thickness (m)
of the KN Group
(Early Cretaceous)
0 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
700 - 800
800 - 900
> 900
0 10 20 30 40 50 km
1:1421085

Figure A-7:

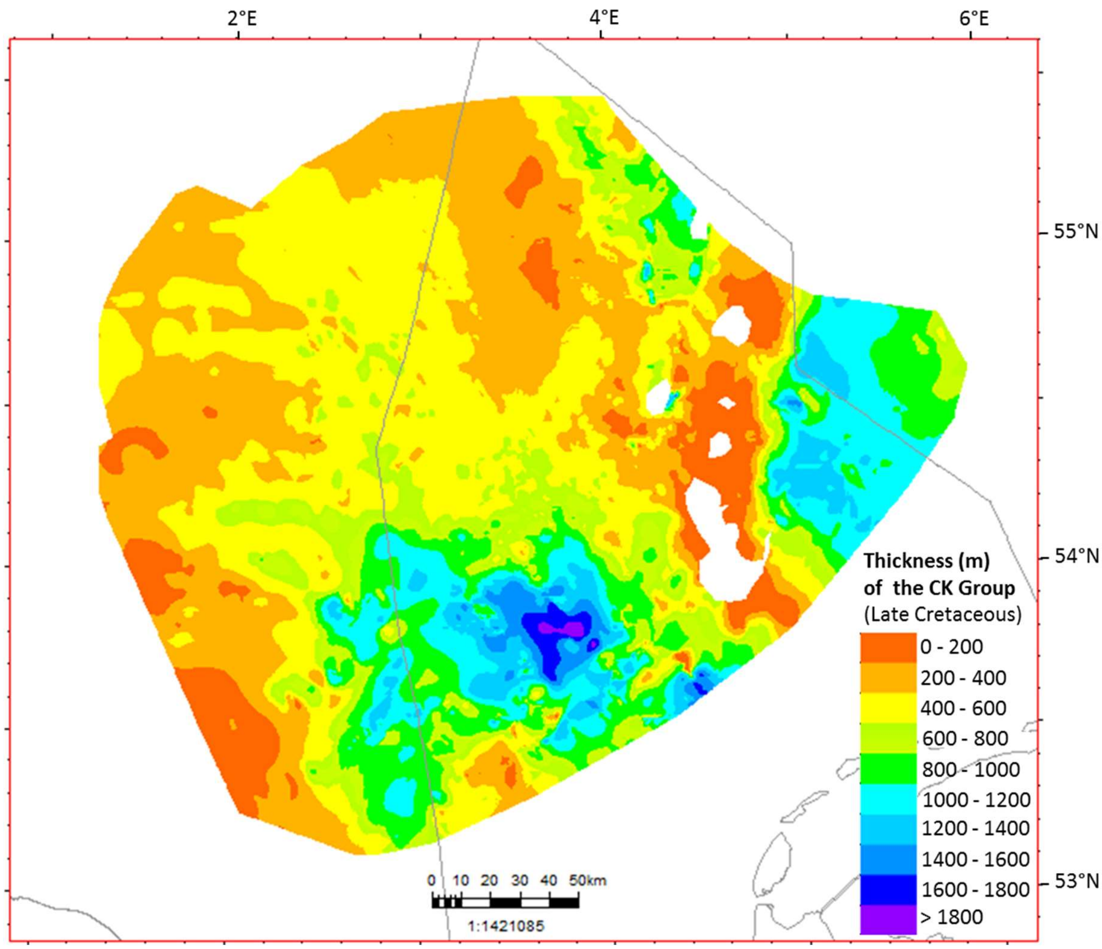

2°E
4°E
6°E
55°N
54°N
53°N
Thickness (m)
of the CK Group
(Late Cretaceous)
0 - 200
200 - 400
400 - 600
600 - 800
800 - 1000
1000 - 1200
1200 - 1400
1400 - 1600
1600 - 1800
> 1800
0 10 20 30 40 50km
1:1421085

Figure A-8:

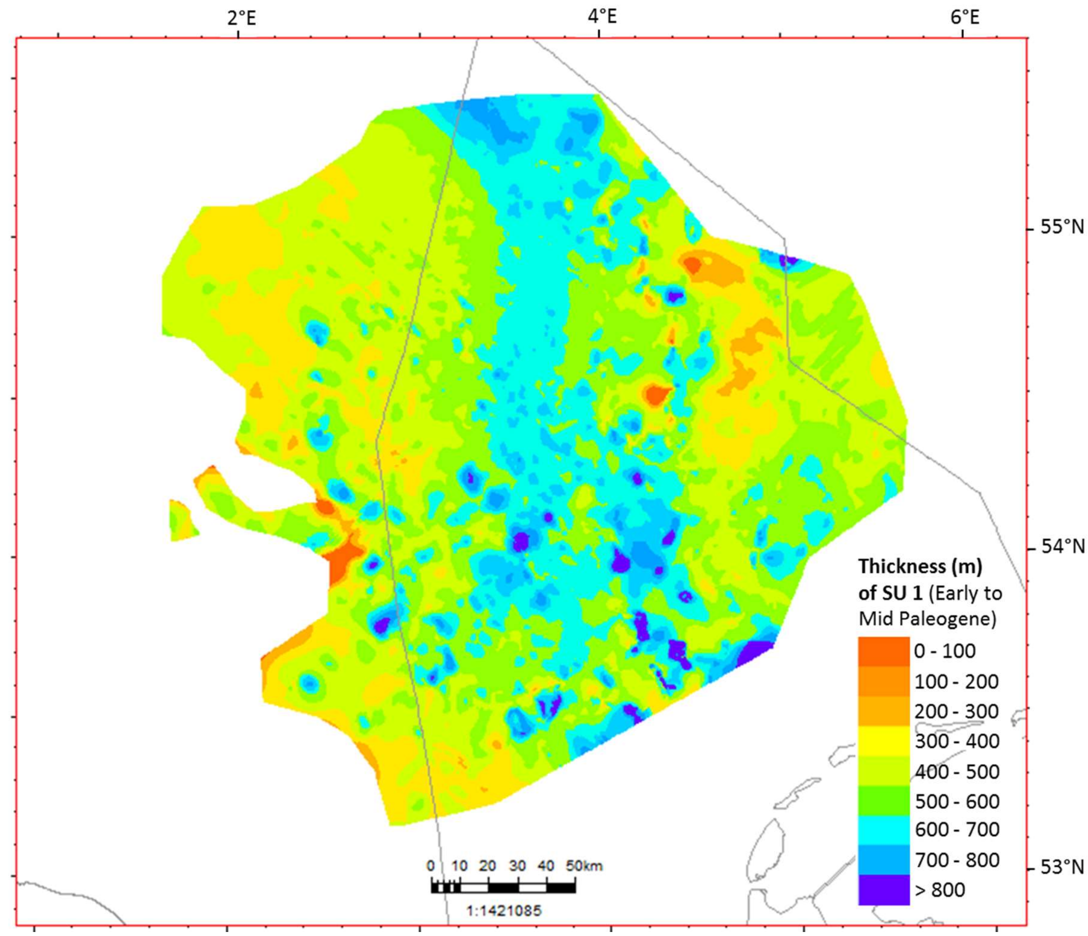

2°E
4°E
6°E
55°N
54°N
53°N
0 10 20 30 40 50km
1:1421085
Thickness (m) of SU 1 (Early to Mid Paleogene)
0 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
700 - 800
> 800

Figure A-9:

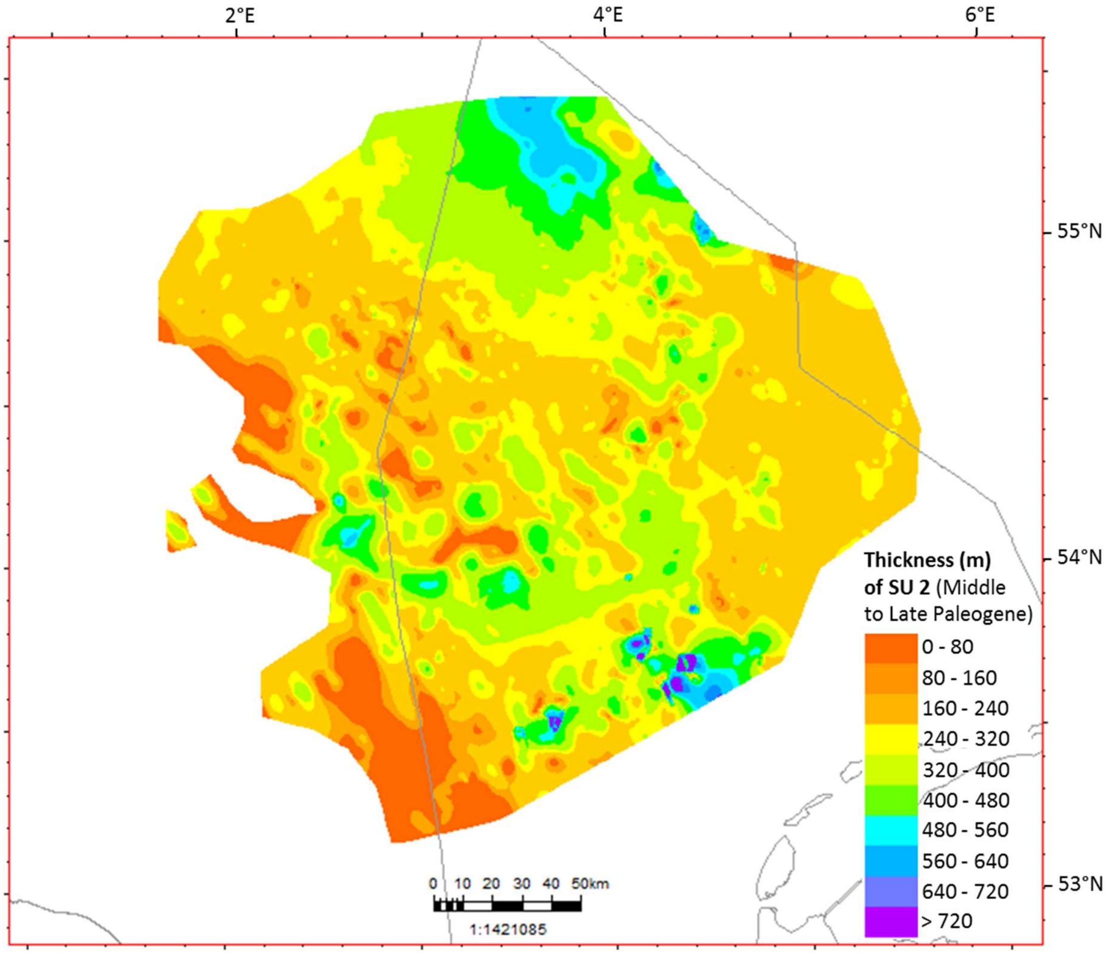
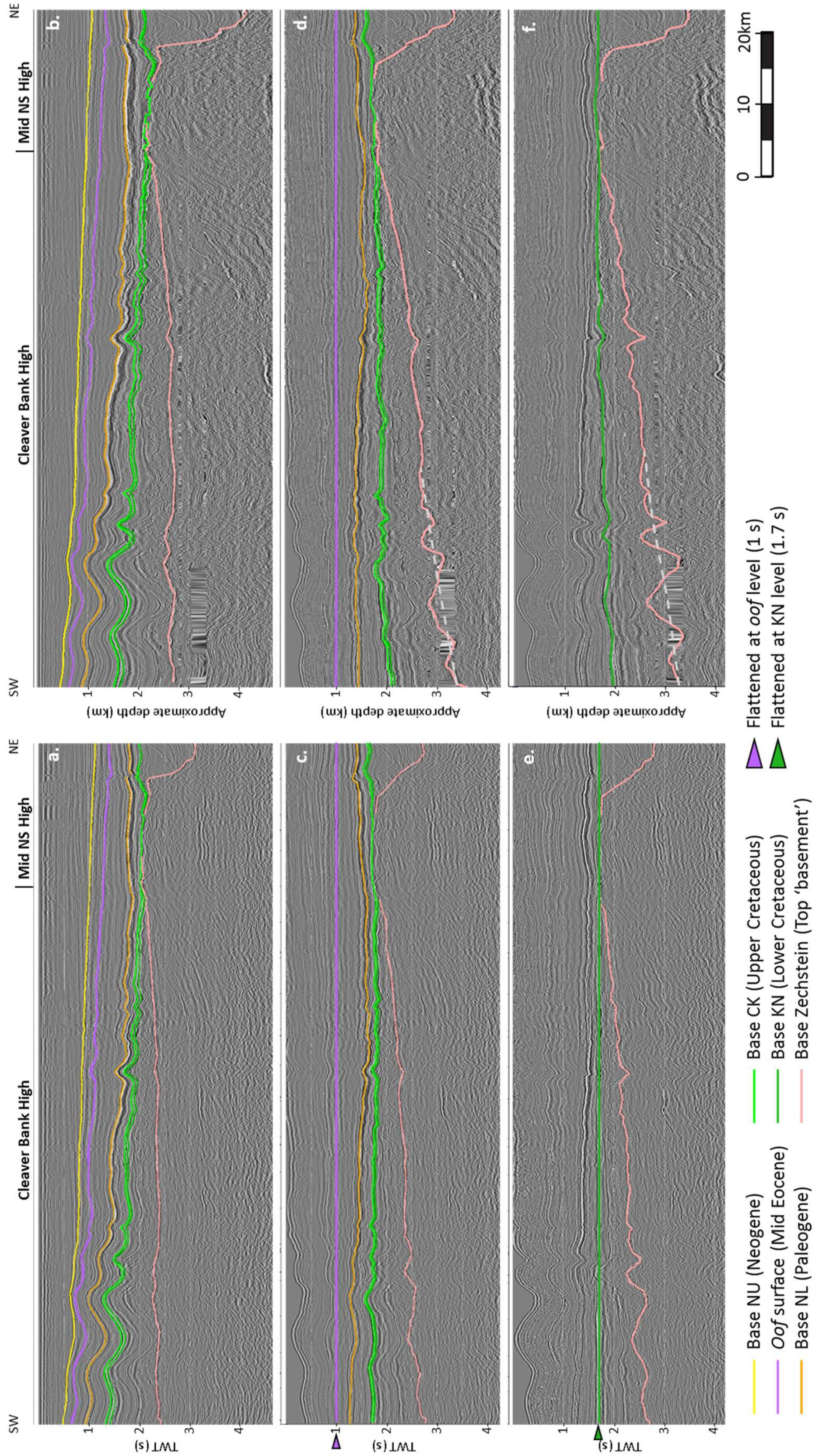

2°E
4°E
6°E
55°N
54°N
53°N
0 10 20 30 40 50km
1:1421085
Thickness (m) of SU 2 (Middle to Late Paleogene)
0 - 80
80 - 160
160 - 240
240 - 320
320 - 400
400 - 480
480 - 560
560 - 640
640 - 720
> 720

Figure A-10:



SW
NE
Cleaver Bank High
Mid NS High
a.
b.
c.
d.
e.
f.
TWT (s)
Approximate depth (km)
0
10
20km
Base NU (Neogene)
Oof surface (Mid Eocene)
Base NL (Paleogene)
Base CK (Upper Cretaceous)
Base KN (Lower Cretaceous)
Base Zechstein (Top 'basement')
Flattened at oof level (1 s)
Flattened at KN level (1.7 s)