



**Microfossil and nannofossil analysis
of the Upper Cretaceous to Lower Paleogene interval
from two wells in the locality of the U.K. North Sea 'Silverpit Crater'**

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Abstract: Micropaleontological and nannopaleontological analyses have been carried out on ditch cuttings samples from two wells (Arco British 43/24-3 and British Gas 43/25-1), which penetrated the 'Silverpit Crater' structure in the Southern North Sea Basin (UK Sector). A stratigraphic gap (within the limits of resolution imposed by sampling constraints) has been identified between chalky limestones of Maastrichtian age, which are overlain by sediments of latest Paleocene age or younger. Accepting an impact-origin for the structure, the gap represents an impact-event, which occurred almost certainly post Cretaceous and Early Paleocene times and thus probably within the Late Paleocene, close to the Paleocene-Eocene boundary, ruling out an association with the K/P extinction impact. In well 43/25-1 a short interval of mixed microfaunas and nannofloras was observed, which is suggested as being related to 'resurgence deposits' entering the crater immediately after the impact-event.

Keywords:

- Paleogene;
- United Kingdom;
- Silverpit;
- biostratigraphy;
- impact-crater;
- Foraminifera;
- nannoplankton

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Résumé : Analyse des microfossiles et des nannofossiles de l'intervalle Crétacé supérieur à Paléogène inférieur à partir de deux puits dans la localité du 'cratère de Silverpit', Mer du Nord (Royaume-Uni).- Des analyses micropaléontologiques et nanopaléontologiques ont été réalisées sur des échantillons de déblais de forage provenant de deux puits (Arco British 43/24-3 et British Gas 43/25-1) ayant traversé la structure du 'cratère de Silverpit' dans le bassin méridional de la mer du Nord (secteur britannique). Une lacune stratigraphique (dans les limites imposées par les contraintes d'échantillonnage) a été identifiée entre des calcaires crayeux d'âge Maastrichtien, recouverts par des sédiments d'âge Paléocène supérieur ou plus jeunes. Si on accepte une origine de type impact pour cette structure, cette lacune représente un événement qui s'est presque certainement produit postérieurement au Crétacé et Paléocène inférieur, probablement au Paléocène supérieur, aux environs de la limite Paléocène-Éocène, excluant une association avec l'impact responsable de l'extinction K/P. Dans le puits 43/25-1, un court intervalle avec des microfaunes et nannoflores mixtes a été observé ; il s'agirait de 'dépôts de reflux' correspondant à des sédiments pénétrant dans le cratère immédiatement après l'événement d'impact.

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**Mots-clefs :**

- Paléogène ;
- Royaume-Uni ;
- Silverpit ;
- biostratigraphie ;
- cratère d'impact ;
- foraminifères ;
- nannoplancton

1. Introduction

Origins and Location

Debate on the impact theory of the end Cretaceous extinction event was initiated by the now famous 'ALVAREZ paper' (e.g., ALVAREZ *et al.*, 1980, 1983), which proposed collision with an extra-terrestrial object as a possible mechanism to account for global biotic extinction patterns observed at the end of Cretaceous times. Further stimulus to the debate in the U.K. has been prompted by the identification of (what was at the time) a 'candidate' Cretaceous - Paleogene (K/P) impact crater in sediments beneath the North Sea (STEWART & ALLEN, 2002; ALLEN & STEWART, 2003).

STEWART and ALLEN (based on their data) suggested that the age of the impact was probably around the K/P boundary, which, in the light of the controversy over the status of the Chicxulub Crater in Mexico (KELLER, 2003) and with the suggestion that the end-Cretaceous extinctions were partially caused by multiple impacts, would make it especially interesting. WALL *et al.* (2008) proposed a Middle Eocene age for the North Sea impact based primarily on seismic characteristics and quoting a *pers. comm.* from one of us (MB) of a Middle Eocene age based on preliminary results from the present analysis (which are herein somewhat revised). Clearly, establishing the exact age for the 'Silverpit Crater' impact (as it is now known and named after a nearby seafloor channel feature) would be critical in the evaluation of this structure in those terms.

The Silverpit Crater (Fig. 1) was identified from re-processed 3D seismic data and consists of a c. 20 kilometre diameter crater with at least 10 distinctive concentric rings located between 2 and 10 km from the crater centre. The structure is located approximately 130 km east of Flamborough Head, England (54°14'N 1°51'E) and vertically the structure spans a depth range of 300 m to 1500 m below the current seabed. The seismic data revealed a number of aspects of the structure including a conical central peak within a 3 km diameter inner crater, which is, in turn, bounded by a set of several inward-facing concentric fault scarps (STEWART & ALLEN, 2002, p. 521).

An impact-origin for the Silverpit Crater is one hypothesis although other plausible origins have been proposed, notably UNDERHILL (2004, 2009) proposing a salt-withdrawal mechanism to account for the structure. SMITH (2004) suggests the

structure may be the result of a Paleogene pull-apart basin linked to strike-slip faulting in the Carboniferous basement. CONWAY and HASZELDINE (2005) disputed both theories, proposing that the Silverpit structure exhibits many features including ring faults and synclinal structures that would suggest an extra-terrestrial origin. STEWART and ALLEN (2005) demonstrated, using high resolution seismic sections, that there was a continuity in the Triassic reflector, which they argued dismissed theories of origin of the structure based on salt kinetics.

Structural background in relation to sampled wells

STEWART and ALLEN (2002) identified three distinctive structural zones according to radial distance from the centre (Fig. 1.B):

- **Zone 1 ('Crater Zone'):** A bowl-shaped crater approximately 2960 m in diameter (at top-chalk level) excavated into the Cretaceous chalk and which also obliterated the top Chalk Group seismic reflector. This latter feature is taken as evidence by that the impact event post-dates deposition of the youngest chalk.
- **Zone 2 ('Half-graben Zone'):** The interval between 1.5 km and 4 km from the centre is characterised by a set of concentric extensional fault scarps that face the crater of Zone 1. The faults are evenly spaced with separations between 300-500 m, and with maximum displacements of 50 m.
- **Zone 3 ('Graben Zone'):** The interval between 4 km and 10 km from the centre and is characterised by rings of concentric fault-bound graben structures. The faults are steeper than those of Zone 2, so represent less extension towards the central crater.

Evidence of impact deformation extends down into Jurassic shales in Zone 1; the central crater at base-Cretaceous level is approximately 750 m in diameter with a central peak c. 250 m high. However, the faults of Zones 2 and 3 do not appear to penetrate deeper than the lower part of the Cretaceous sequence.



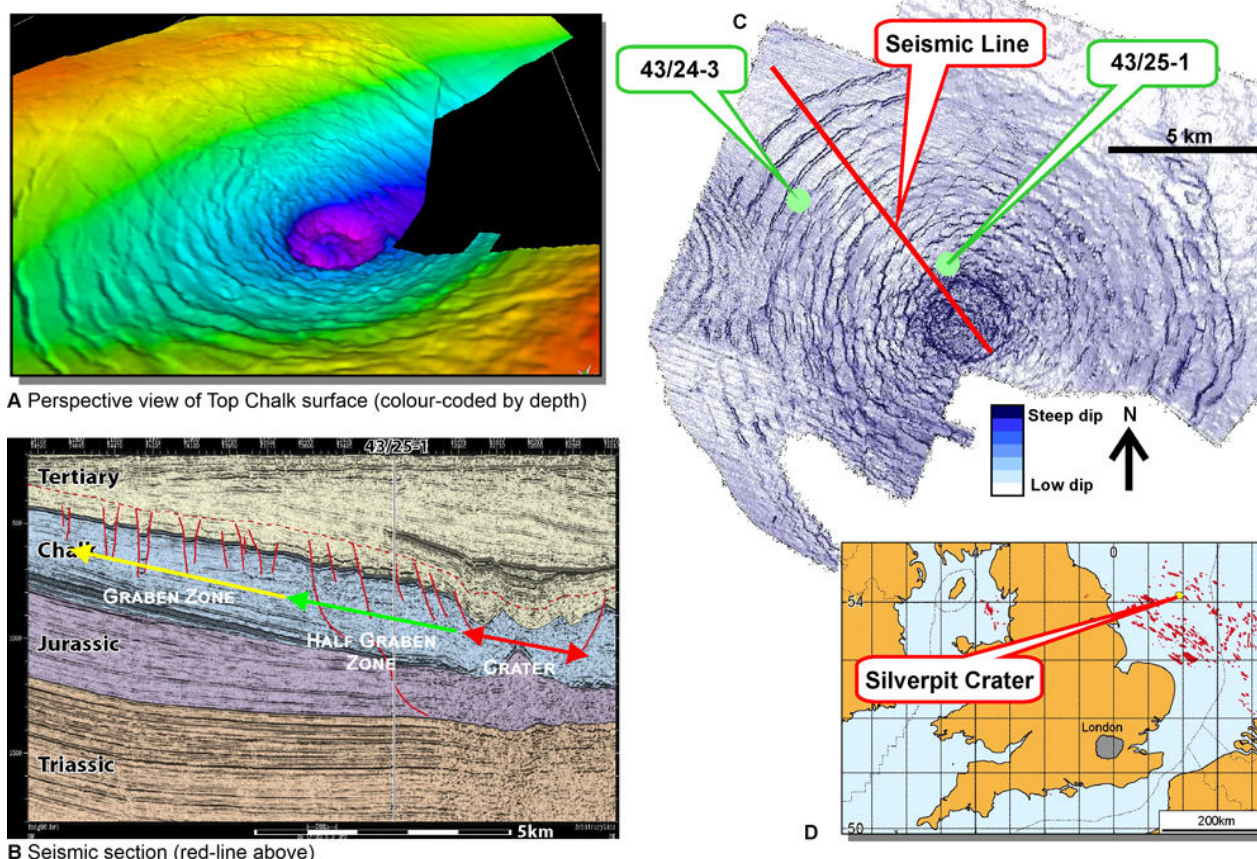


Figure 1: Location and structural details of the Silverpit structure with 3D seismic section on depth with x2 vertical exaggeration (images after STEWART & ALLEN, 2002, 2005).

The particular morphology of the Silverpit impact crater is unusual as it is atypical, in both size and form, compared with other impact-craters observed on Earth and other terrestrial type planets. On the Moon the 'Orientale' multi-ringed basin, and Copernicus Crater (STEWART & ALLEN, 2005) are more typical examples in the lunar setting. STEWART and ALLEN (2002) stated that the closest analogous structure to the Silverpit Crater is the 'Valhalla' Crater on Callisto or the 'Tyre' impact structure on Europa (both moons of Jupiter). However, Silverpit is significantly smaller than any of the known Valhalla-type structures.

Due to the location and depth of burial, direct sampling of the Silverpit Crater sediments has not been possible. However, two commercial wells have penetrated below the K/P boundary within the area-boundaries of the structure in the process of hydrocarbon exploitation. These two wells were designated as 43/24-3 and 43/25-1 and were drilled, respectively, by Arco British Ltd. and British Gas plc. Well 43/25-1 is located within Zone 2 of the Silverpit structure whereas well 43/24-3 is close to the edge of the whole structure in Zone 3. Both wells occur within the north-west quadrant of the entire crater zone (Fig. 1.C) and some well/engineering data for both wells is shown in Table 1.

Parameter	43/24-3 (ARCO British Ltd.)	43/25-1 (British Gas)
Spud date	29 March 1993	17 July 1984
Interval of interest	1400' - 2000'	1560' - 2600'
Hole diameter	16"	26"
Nearest casing point above section	590' (conductor, diameter unknown)	408' (30")
Type of mud	KCL polymer	Unknown
Type of drill-bit	Unknown	Unknown
Caliper log	Unknown	Not run

In common with British usage at time of drilling, the abbreviation for feet = ', for inches = " 1 foot = 0.3048 metres, 1 inch = 0.0254 metres. These abbreviations are also used in the text.



Sampling and problems associated with the available material

Both wells were drilled to reach Paleozoic targets and therefore the Cenozoic-Mesozoic section was considered as 'overburden' by the operating companies. Sampling intervals are 50' in the 43/24-3 well and 20' in the 43/25-1 well in the interval of interest herein. Ditch cutting samples from these types of wells are subject to a number of problems in comparison to standard field samples.

The most serious of these is caving: that is, contamination of rock fragments generated by the bit by material detaching from the open lithological units of the well above the drilling bit. The drilling mud circulates by travelling down the drillpipe, through the jets of the drilling bit and then up and out of the well between the drillpipe and the exposed rock of the well. Due to the release of pressure on the rock by the drilling of the well, sediments 'squeeze into' the open well to some extent or other. When the sediment is brittle, it may fracture off as small shards, which get included in with freshly cut material from lower down in the well. This effectively can contaminate nominally *in situ* rock fragments (containing nominally *in situ* microfossils), with fragments (and microfossils) from younger strata.

This contamination only allows the industrial biostratigrapher to use the first (or highest) downhole occurrence - FDO (=last local evolutionary appearance) of a species, or an acme of that species as reliable as datum levels. The last (or lowest) downhole occurrence of a species (equating to the first evolutionary appearance of that species in the area) can be artificially extended downwards due to caving and such events are conferred with much less confidence as biostratigraphic marker events.

A second problem with ditch cutting samples is that depending on its composition, the drilling mud can be highly destructive to any micro and nanofossils present in the cut sediments. SELF-TRAIL and SEEFERT (2005) showed that severe dissolution to nanofossils can occur in wet ditch cutting samples, with commonly between 50% and 100% loss of specimens over a 222 day period. Similar high rates of dissolution have also been noted by us in calcareous Foraminifera from ditch cutting samples. There is no indication of how long the samples used in this study were stored as wet ditch cuttings but the two wells were drilled between 1984 and 1993 and thus some sample degradation might be expected.

For this study, a limited number of 'washed-and-dried' ditch cuttings samples were made available, curated by the British Geological Survey in Edinburgh, from the 2 'intra-structure' wells. These samples had been washed immediately after collection at the wellsite to remove as much drilling fluid as possible, then immediately oven dried. (N.B. between 2011-2012 the entire contents of the Edinburgh core store were relocated to BGS Keyworth). The sample sets span the boundary

between the main Cretaceous carbonate (chalk) sequence and the overlying Tertiary clastics.

Samples available for analysis were:

- **43/24-3** (13 cuttings samples at 50 feet intervals):
1400' 1450' 1500' 1550' 1600' 1650'
1700' 1750' 1800' 1850' 1900' 1950'
2000'
- **43/25-1** (21 cuttings samples at 20 feet intervals):
1560' 1580' 1600' 1620' 1640' [sample gap] 2300' 2320' 2340' 2360' 2380' 2400'
2420' 2440' 2460' 2480' 2500' 2520'
2540' 2560' 2580' 2600'

Note - the sampling interval was determined by the well's operator at the time of drilling and was not chosen by the authors. They were collected on the drilling rig during periods of active drilling and their nominal sample depths are the result of calculations that depend on a variety of drilling and equipment parameters and are subject to possible/probable error. Nevertheless, these samples represent the only material available from the stratigraphic interval of interest. In all cases the volume of sample material available to the authors was very small, in the order of 10-20 grammes per sample. Routine paleontological preparations in this respect normally use a minimum of 100 grammes.

The samples were analysed for micropaleontology and calcareous nannoplankton (with the majority of the sample material being used for the former). This would allow a biostratigraphic framework to be provided within which the Siverpit structural signal might be placed and thus determine its approximate age.

Microfossil sample preparation

Standard microfossil preparation techniques were followed: the sample material was washed over a 63-micron sieve with running water and the residue oven-dried at approximately 150°C. The residue was separated into size fractions by dry-sieving and completely picked for microfossils.

Nannofossil sample preparation

Due to the very small amount of raw material remaining after the microfaunal preparations had been made, nannofossils sample preparations were made using simple smear sample technique of a very small amount of mixed cuttings (BOWN & YOUNG, 1998). The preparations were fixed using Norland Optical Adhesive.

2. Results

Benthic Foraminifera

Both agglutinated and calcareous benthic Foraminifera are well represented in the samples from both study wells and form the dominant component of both Late Cretaceous and Paleogene microfaunal assemblages. In the Upper Cretaceous samples, benthic Foraminifera comprise ≥90% of the total assemblage and of these the



calcareous benthic taxa form the dominant component. The preservation is, in most cases, remarkably good.

Planktonic Foraminifera

Planktonic Foraminifera are poorly represented in well 43/25-1. They are rare and localised in the Upper Cretaceous samples, moderately common near the upper limit of the limestones (see further comments below) and rare in the Paleogene samples. They are more commonly recorded in the 43/24-3 well in both Upper Cretaceous and Paleogene samples. This observation suggests that paleodepths were somewhat greater over the 43/24-3 well location than well 43/25-1, although the wells are less than 10 km apart. However, the maximum percentage of planktonic Foraminifera recorded in any sample from 43/24-3 is c. 10%, which suggests that paleodepths were, probably, around an inner to middle neritic setting.

Calcareous nannoplankton

Nannofossil recovery in the 43/24-3 well was extremely poor. Nannofossil preparations from this well were either barren or contained an insufficient number of specimens to allow valid biostratigraphic observations to be made.

It is suggested that the poor nannofossil recovery was due to post collection dissolution of carbonate material in the chemically aggressive environment of the drilling mud used in cutting of this particular well.

Preparations made from the 43/25-1 well samples contained nannofloras with abundances and diversity considered normal for this stratigraphic interval in the North Sea.

Other fossils

Diatoms and ostracods were rare to moderately common in the samples studied. Pyritised diatoms were moderately common from the Paleogene samples in both wells, whereas ostracods (mainly in well 43/24-3) were recorded only in Upper Cretaceous samples. Radiolaria were only recorded from Early Eocene and younger sediments in the 43/25-1 well.

Macrofossil debris was very commonly observed with abundant bryozoan, bivalve (*Inoceramus*) and echinoid debris recorded in most of the Cretaceous samples. Sponge spicules (including *Rhaxella* spp.) were sporadically recorded.

3. Biostratigraphy of well 43/24-3

Biostratigraphic zonation in this study utilises the published schemes of various authors. For the Tertiary sediments the two-fold scheme of KING (1989) is used for the foraminiferal data (NSP zones - North Sea Planktonic and NSB zones - North Sea Benthic) and the basal Paleogene North Sea nannofossil scheme (NNTp/NNTe) of VAROL (1998) is used for the calcareous nannoplankton.

For the Cretaceous sediments, the combined scheme of KING *et al.* (1989) is used for the foraminiferal data (FCS zones - Foraminifera Cretaceous Shelf or South), and the UC zonation of BURNETT (1998) has been used for nannofossils.

The zones of KING (1989) and KING *et al.* (1989) are based primarily on foraminiferal bioevents. However, significant events based on radiolaria and diatom species/assemblages are also utilised.

Results of micro- and nannofossil analyses from this well are shown in Figure 2.

- 1400' - 1450': ?Middle Eocene, ?Lutetian, no foraminiferal zones assigned, nannofossil zones NNTe8 - NNTe9 (top not seen)

Microfossils: The single sample analysed at 1400' yielded only moderately common calcareous benthic Foraminifera comprising *Astacolus* spp., *Fronicularia* spp., *Lenticulina cultrata* (MONTFORT), and *Nodosaria* spp. together with rare indeterminate forms.

Nannofossils: Based on a poor nannoflora at 1400', which included *Chiasmolithus medius* PERCH-NIELSEN, *Ch. solitus* (BRAMLETTE & SULLIVAN), *Laternithus minutus* STRADNER, *Reticulofenestra dictyoda* (DEFLANDRE in DEFLANDRE & FERT), *Pontosphaera pulcheroides* (SULLIVAN), *Neococcolithes dubius* (DEFLANDRE in DEFLANDRE & FERT), and *Nannoturba robusta* MÜLLER, an Early Lutetian (NNTe8-NNTe9) age is proposed.

- 1450' - 1550': Lower Eocene, Ypresian, foraminiferal zones NSP5-NSP4, NSB3-?NSB2

Microfossils: Three samples (1450', 1500', and 1550') were analysed from this interval and microfossil recovery was good. Calcareous benthic taxa recorded were *Lenticulina cultrata*, *Anomalinoides rugosa* (PHLEGER & PARKER), *Bulimina midwayensis* CUSHMAN & PARKER, *Cibicides* spp., *Uvigerina* spp., *Cibicidoides* spp. *C. eocaenus* (GÜMBEL), *Eponides* spp., *Osangularia* spp., and *Vaginulinopsis decorata* (CUSHMAN). Some minor caving was also observed and rare specimens of *Stensioeina pommerana* BROTZEN were recorded in the sample at 1550'. This Late Cretaceous species is thought to be re-worked at this depth.

Agglutinated Foraminifera were only recorded from the sample at 1550' and comprised *Ammodiscus* spp., *Reticulophragmium amplexans* (GRZYBOWSKI), *Lagenammina* spp., *Rhabdammina* spp., *Spiroplectammina spectabilis* (GRZYBOWSKI), and *Usbekistania charoides* (JONES & PARKER).

Planktonic Foraminifera were moderately common throughout this interval and included *Globorotalia pseudobulloides* (PLUMMER), *Gl. cf. pseudobulloides*, *Subbotina triloculinoides* (PLUMMER), *S. cf. triloculinoides*, *S. linaperta* (FINLAY), *Pseudohastigerina wilcoxensis* (CUSHMAN & PONTON), and *Globigerina* spp.

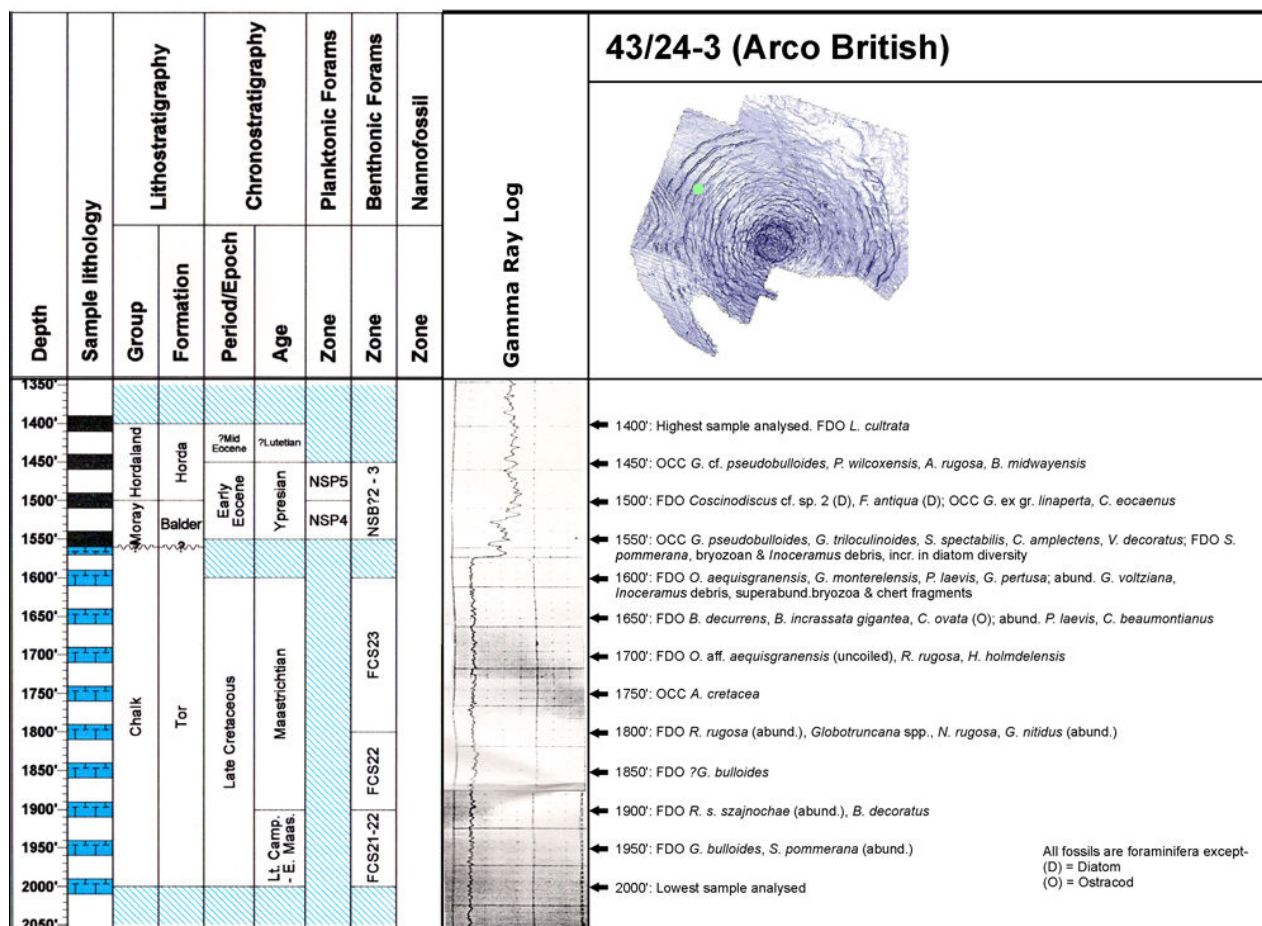


Figure 2: Summary of microfossil and nannofossil results from well 43/24-3. The log data scale is unknown as only a paper extract was made available.

Diatoms were also commonly recorded from this interval and included stratigraphically useful taxa such as *Fenestrella antiqua* (GRUNOW) (= *Coscinodiscus* sp. 1 of KING, 1983) and *Coscinodiscus* sp. 2 *sensu* THOMAS & GRADSTEIN in KING (1983) (see BIDGOOD *et al.*, 1999, for a review of North Sea diatom biostratigraphy and taxonomy).

Nannofossils: Nannofossil preparations from this interval were found to be barren of nannofloras.

- 1600' - 1900': Upper Cretaceous, Maastrichtian, foraminiferal zones FCS23-FCS22

Note: The lithostratigraphic boundary between the limestones of the Chalk Group and the overlying clastic sequences (of the Moray and Hordaland Groups) was picked at 1560' in this well based on wireline log data.

Microfossils: Six samples (1600', 1650', 1700', 1750', 1800', and 1850') were analysed from this interval and microfaunal recovery was excellent. Calcareous benthic taxa recorded were *Stensioeina pommerana*, *Gavelinella monterelensis* (MARIE), *G. nobilis* (BROTZEN), *G. pertusa* (MARSSON), *G. voltziana* (ORBIGNY), *Gyroidinoides nitidus* (ORBIGNY), *Lenticulina* spp., *Nodosaria* spp., *Osangularia navarroana* (CUSHMAN), *Praebulimina laevis* (BEISSEL), *Pr. obtusa* (ORBIGNY), *Bolivina decurrens* (EHRENBERG), *B. incrassata gigantea* WICHER, *Cibicides beaumontianus* (ORBIGNY),

Lagena striata (ORBIGNY), *Pullenia bulloides* (ORBIGNY), *P. quaternaria* (REUSS), *Eouvigerina aculeata* (EHRENBERG), *Guttulina problema* (ORBIGNY in EGGER), *Bolivinoidea draco* (MARSSON), *B. laevigatus* MARIE, *B. milliaris* HILTERMANN & KOCH, *Eponides beisselli* SCHIJFSMA, and *Neoflabellina rugosa* (ORBIGNY).

Agglutinated Foraminifera were also common and included *Arenoturispirillina* spp., *Ataxophragmium variable* (ORBIGNY), *Marssonella* spp., *Orbignya aequigranensis* (BEISSEL), *O. aff. aequigranensis*, *Tritaxia* spp., and *Arenobulimina* spp.

Planktonic Foraminifera were common to abundant and included *Hedbergella holmdelensis* OLSSON, *Rugoglobigerina rugosa* (PLUMMER), *Archaeoglobigerina cretacea* (ORBIGNY), *Globotruncana* spp., and questionable *Gl. bulloides* VOGLER.

Other microfossils recorded from this interval included the ostracods *Cytherella ovata* (ROEMER), *Bairdia* spp., and *Cytheropteron* spp. *Inoceramus* (bivalve) prisms, bryozoan debris, and echinoid debris were also recorded in abundance. Sponge spicules (tetraxons and *Cricaster* spp.) were also recorded.

Nannofossils: Apart from the sample at 1700', nannofossil preparations in this interval were found to be barren. At 1700', single specimens of *Helicolithus trabeculatus* (GORKA), from the Late Cretaceous, and *Chiasmolithus expansus* (BRAM-



LETTE & SULLIVAN), from the Middle Eocene to basal Oligocene, were stratigraphically inconclusive.

- 1900' - 2000': Upper Cretaceous, Lower Maastichtian - Upper Campanian, foraminiferal zones FCS22-FCS21, (base not seen)

Microfossils: Three samples (1900', 1950', and 2000') were analysed from this interval and microfaunal recovery was excellent. Calcareous benthic taxa recorded were similar to those recorded from the interval above, with the addition of *Bolivinoidea decoratus* (JONES) and *Reussella szajnochae szajnochae* (GRZYBOWSKI). *Gavelinella nobilis* and *Neoflabellina rugosa* (recorded from above) were however, not recorded from this interval.

All the agglutinated Foraminifera recorded above were likewise recorded from this interval as were the planktonic Foraminifera. However, in addition, a single specimen of *Rotalipora* spp. was recorded in the lowest sample from this interval (2000').

Other microfossils recorded from this interval were also similar to those recorded above.

Nannofossils: Nannofossil preparations from this interval were found to be barren of nannofloras.

4. Biostratigraphy of well 43/25-1

Results of micro- and nannofossil analyses from this well are shown in Figure 3.

- 1560' - 1640': Middle Eocene, Lutetian, foraminiferal zones ?NSP7, ?NSB5 (top and base not seen)

Microfossils: Five samples were analysed between 1560' - 1640'. Although no age-diagnostic taxa were recorded, the presence of abundant *Pseudohastigerina wilcoxensis* (CUSHMAN & PONTON) (planktonic Foraminifera) together with benthic Foraminifera *Vaginulinopsis decoratus* (REUSS), *Nodosaria ?latejugata* GÜMBEL, and *Bolivinoidea ?adamsi* (LALICKER) tentatively suggests a Middle Eocene age.

Nannofossils: Samples in this interval were not analysed for nannofossils.

A sample gap of approximately 650 feet occurred at this point.

- 2300' - 2360': Lower Eocene, Ypresian, foraminiferal zones ?NSP5-NSP4, NSP4, ?NSB3, ?NSB2, nannofossil zones NNTe 6-7B (top not seen)

Microfossils: Four samples (2300', 2320', 2340', and 2360') were analysed from this interval and microfaunal recovery was good. Calcareous benthic taxa recorded were *Nodosaria* spp., *N. latejugata*, *Gyroidina* spp., *Lenticulina* spp., *L. cultrata*, *Dentalina* spp., *Cibicoides eocaenus*, and *Fronicularia* spp.

Agglutinated Foraminifera were also commonly recorded from this interval and comprised *Clavulina anglica* (CUSHMAN), *Haplophragmoides* spp.,

Rhabdammina spp., *Ammodiscus cretaceus* (REUSS), *Glomospirella* spp., *Reophax* spp., *Usbekistania charoides*, *Ammobaculites* spp., and questionable *Trochammina challenger* HEDLEY et al., as well as common indeterminate (deformed) specimens.

Planktonic Foraminifera were rare throughout this interval and included *Globigerina* spp. and a single questionable specimen of *Globoconusa daubjergensis* BRÖNNIMANN. A single specimen of the Late Cretaceous taxon *Globigerinelloides* spp. was also recorded.

Diatoms were also commonly recorded from this interval and included the stratigraphically useful *Fenestrella antiqua* and *Coscinodiscus* sp. 2 (see section 1450'-1550' above).

Nannofossils: At 2300', the nannoflora included *Toweius occultatus* (LOCKER) suggesting an age no younger than Early Eocene, Ypresian (NNTe 6-7B zones). Other species at this depth and through the interval were long ranging species, which in general terms supported this age. Prominent amongst these were *Reticulofenestra dictyoda*, *Sphenolithus radians* DEFLANDRE in GRASSE, and *Discoaster lodoensis* BRAMLETTE & RIEDEL. At 2320', the occurrence of *Tribrachiatulus orthostylus* SHAMRAI supported this age.

Low numbers of reworked Late Cretaceous species were recorded in this interval. They tended to be the more robust forms such as *Micula decussata* VEKSHINA, *Arkhangelskiella cymbiformis* VEKSHINA, *Prediscosphaera cretacea* (ARKHANGELSKY), and *Eiffellithus gorkae* REINHARDT.

- 2380' - 2400': 'Mixed' Paleocene and Cretaceous, foraminiferal zone ?NSB2, nannofossil zone ?NNTp8

The lithostratigraphic boundary between the limestones of the Chalk Group and the overlying clastic sequences (of the Moray and Hordaland Groups) was picked at 2392' in this well based on wireline log data.

Microfossils: The sample at 2380', several feet above the top of the Chalk Group, is significant as the microfaunal assemblage is unique compared with other samples from this well. The assemblage is of mixed Paleogene and Late Cretaceous Foraminifera including *Bulimina* cf. sp. A (KING), *B. midwayensis*, *Nodosaria* spp., *Globigerina* spp., and *Pseudohastigerina wilcoxensis* from the Paleocene - Eocene and *Gavelinella voltziana*, *G. pertusa*, *Orbignyana aequisgranensis*, *Archaeoglobigerina cretacea*, *Globigerinelloides asper* (EHRENBERG), and *Hedbergella* spp. from the Late Cretaceous. The three Late Cretaceous planktonic Foraminifera are especially significant as none were recorded from the interval immediately below.

In addition, Paleogene diatoms including *Fenestrella* cf. *antiqua* (recorded on chart as *Coscinodiscus* cf. sp. 1 *sensu* KING), were also recorded at 2380'.

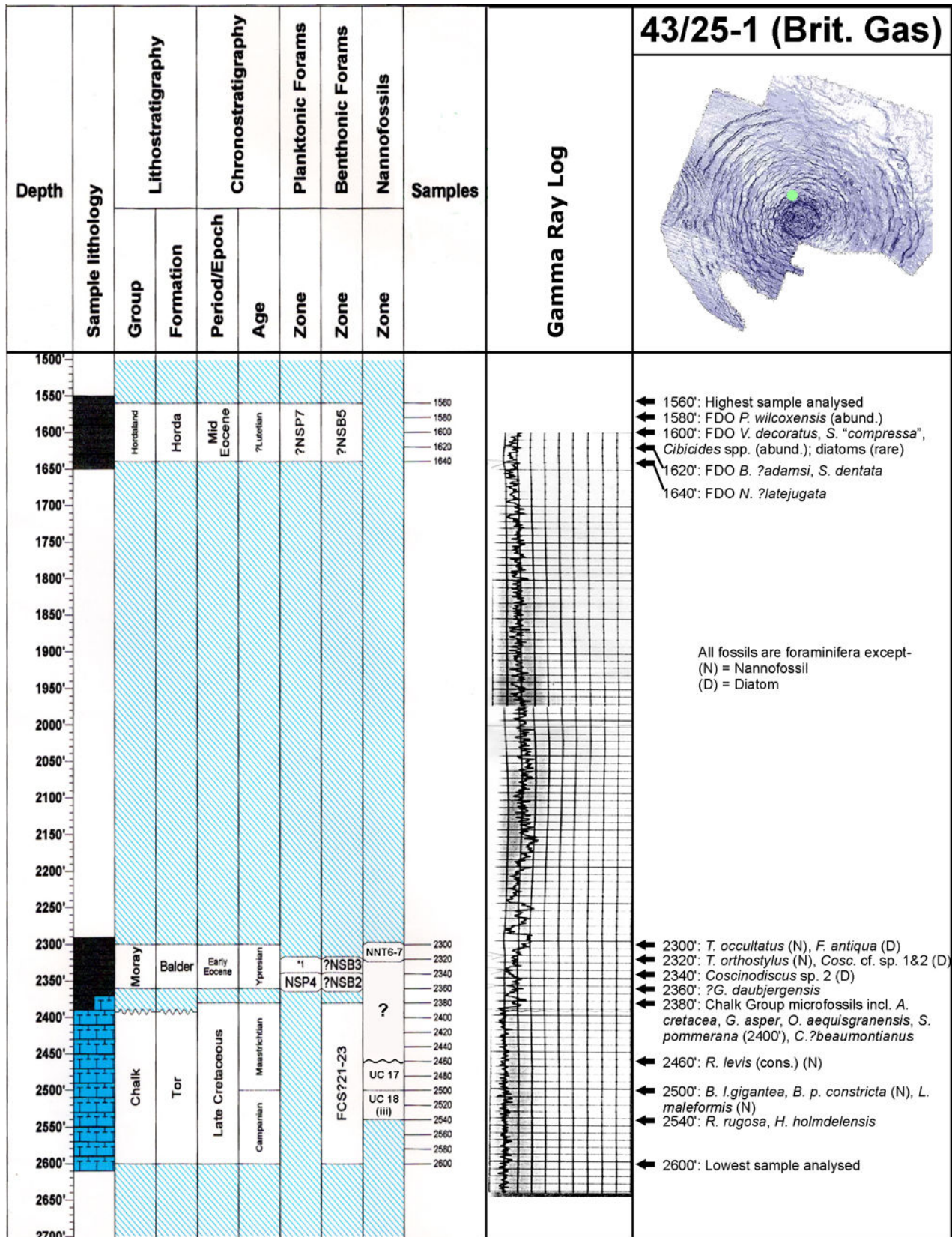


Figure 3: Summary of microfossil and nannofossil results from well 43/25-1. The log data scale is unknown and only a paper extract was made available.

This assemblage would, in the normal course of events, be taken as simply the result of local reworking, but an alternative explanation for its occurrence is given below.

Nannofossils: As with the microfauna at 2380', the nannoflora from 2400' is unique. The dominant component consisted of relatively long ranging Late Cretaceous species. Amongst these



were *Kamptneria magnificus* DEFLANDRE, *A. cymbiformis*, *M. decussata*, and *Prediscosphaera cretacea*. However, other more significant species were *Gartnerago obliquum* (STRADNER) (FDO UC19i), *Cribrosphaerella daniae* PERCH-NIELSEN (full range intra UC20), and *Calculites obscurus* (DEFLANDRE) (FDO UC19ii).

A second subsidiary but still significant component of the nannoflora was from the Paleocene. The presence of *Prinsius dimorphosus* (PERCH-NIELSEN), *Cruciplacolithus primus* PERCH-NIELSEN, *Cruciplacolithus tenuis* (STRADNER), and *Fasciculithus tympaniformis* HAY & MOHLER in HAY *et al.* are evidence that Paleocene sediments were present in the well, between 2360' and 2380'. GALLAGHER (1990) recorded *F. tympaniformis* as restricted to his Upper Paleocene NS16 zone (topmost NNTp8). The top of the range of *Prinsius dimorphosus* is also at the top of the NNTp8 zone.

Amongst the Upper Cretaceous nannofossils, rare, distorted specimens of *Prediscosphaera cretacea* and *Biscutum harrisonii* VAROL were noted. The examples of *Prediscosphaera cretacea* appear to have lost their central spines, have had the two shields partially disconnected and sheared so that they do not precisely lie one on top of the other as they would in undamaged specimens. In addition, the distal shield has been fractured and twisted upwards in a loose spiral.

The specimens of *Biscutum* were also damaged by fracturing in a similar way to *Prediscosphaera cretacea*, fracturing occurring as a clean vertical break along the long axis.

This kind of structural damage has only been recorded previously in multi-rayed species of *Discoaster* (*D. multiradiatus* BRAMLETTE & RIEDEL, *D. lenticularis* BRAMLETTE & SULLIVAN, *D. salisburgensis* STRADNER, and *D. saipanensis* BRAMLETTE & RIEDEL) associated with the Late Eocene, Chesapeake Bay impact-crater, eastern USA (SELF-TRAIL, 2003). This effect is being further explored by JUTSON and SELF-TRAIL (in prep.).

Comment: It may be wondered why similar structural damage is not evident in the (larger) microfossils in contrast to the nannofossils. In routine sample preparations, fragmentary microfossils are not usually picked for further examination unless the entire assemblage is fragmentary. The authors recall no special appearance of the sample residues while picking the assemblages from these chalky samples. We emphasise that this is conjectural but one possible hypothesis is that if the surrounding chalk fabric is not too brittle, then impact stresses may be 'absorbed' by the sediment rather than being conducted through the microfossil itself. The nannofossils, being the principle component of that sediment, experience the impact stresses directly and, thus, fracture.

• 2420' - 2500': Upper Cretaceous, Lower Maastrichtian, foraminiferal zones ?FCS23-21 (part), nannofossil zone UC18-?17

Microfossils: Five samples (2400', 2420', 2440', 2460', and 2480') were analysed from this interval and microfaunal recovery was moderate to good. Calcareous benthic taxa recorded from the Chalk Group in this well were less abundant and diverse than in well 43/24-3 but included *Lenticulina* spp., *Nodosaria* spp., *Dentalina* spp., *Gavelinella* spp. (including *G. voltziana*), *Stensioeina pommerana*, *Cibicoides beaumontianus*, *Gyroidinoides nitidus*, and *Osangularia navarroana*.

Agglutinated Foraminifera were also less common and included *Ataxophragmium variabile*, *Marssonella* spp., *Orbignya aequigranensis*, *Dorothia* spp., and *Trochammina* spp.

Planktonic Foraminifera were absent from this interval. Other microfossils recorded from this interval included *Inoceramus* (bivalve) prisms, bryozoan debris and echinoid debris.

Nannofossils: The first downhole occurrence of dominantly Maastrichtian nannofloras including the species *Reinhardtites levis* PRINS & SISSINGH in SISSINGH, recorded consistently throughout the interval and commonly from 2460' to the base of the interval. The occurrence of a single specimen of *Tranolithus orionatus* (REINHARDT) at 2560' would hint that the top of the UC17 zone had been penetrated, but as a single specimen, the evidence is weak. The consistent and common occurrence of *Reinhardtites levis* suggests an Early Maastrichtian age (UC18 zone).

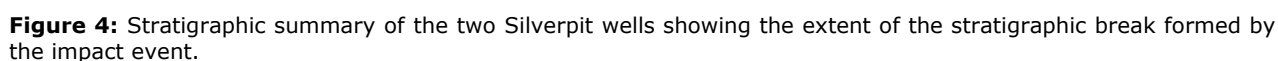
• 2500' - 2600': Upper Cretaceous, Upper Campanian, foraminiferal zones ?FCS23-21 (part), nannofossil zone UC16 (base not seen)

Microfossils: Six samples were analysed from this interval (2500', 2520', 2540', 2560', 2580', and 2600'). Microfaunal recovery was good compared to the interval above, however the assemblages included long-ranging Late Cretaceous species similar to those recorded from the interval above. No definitive Campanian-age taxa were recorded.

Nannofossils: The first downhole occurrences of a nannoflora including *Broinsonia parva constricta* HATTNER *et al.* and *Lucianorhabdus maleformis* REINHARDT at 2500' suggests that the interval is of Late Campanian, UC16 zone age.

5. Discussion

The biostratigraphic results from these wells do not allow a definitive answer regarding an impact origin for the Silverpit structure although the authors are inclined to believe that it is indeed so, based on the presence of shockwave induced fracturing in some nannofossils and the stratigraphy in comparison to adjacent wells (authors' personal observations, e.g., BIDGOOD, 1995, but see also WHITEHEAD *et al.*, 2004). However, the results of this study attempt to show the approximate age of the stratigraphic break between limestones and chalks of the Chalk Group and overlying clastics in this particular part of the North Sea Basin and therefore provide an age for the putative impact event (see Figs. 2-3).



ranging from Late Maastrichtian to earliest Eocene age, which includes sediments attributable to the (from youngest to oldest) Balder (lowermost part), Sele, Lista, Maureen/Vaale, Ekofisk and Tor (uppermost part) Formations (Fig. 4).

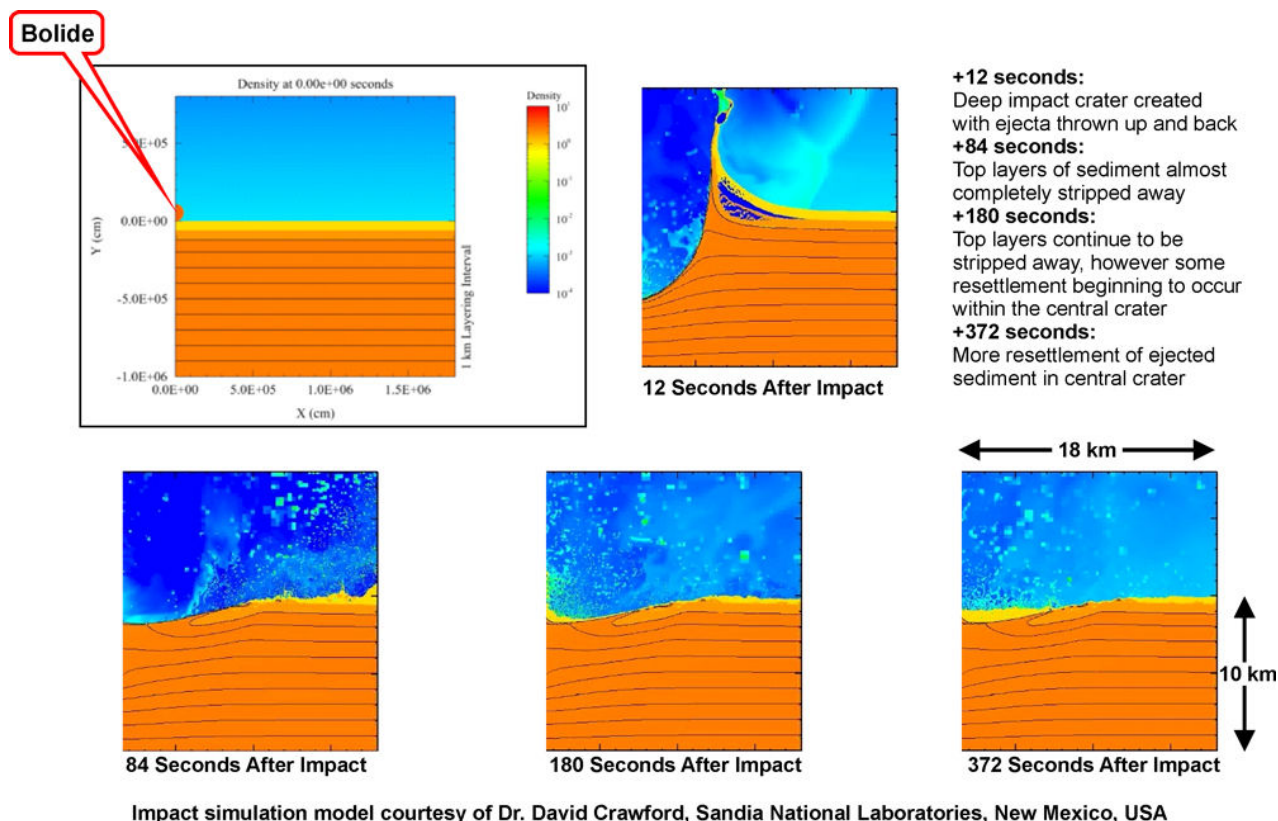


Figure 5: An impact simulation model for a bolide of approximately 1.1 km diameter (courtesy of Dr David CRAWFORD, Sandia National Laboratories, USA).

The section in the 43/25-1 well, which was drilled in the Zone 2, half graben zone of the structure as defined by STEWART and ALLEN (2002) can be divided into three distinct parts. At the base, there is a Campanian to Lower Maastrichtian interval, which appears to be *in situ*. Above this at 2400' and 2380', the samples contained mixed assemblages, which include Late Maastrichtian, Late Paleocene and Eocene components, which would suggest a high degree of sediment mixing. This is denoted in Figure 4 for well 43/25-1 by an interval labelled as 'Mélange Assemblages' to reflect mixed microfaunas recovered from, potentially, a wide stratigraphic range of sediments. Above this is another presumably *in situ* section of sediments of Early Eocene age. The presence of microfossils and nannofossils restricted to the Late Paleocene in the mixed assemblage section implies that the event that caused the Silverpit structure probably occurred post-Selandian times (Middle Paleocene NSB1c/NTTp8) and pre/intra Ypresian times (Lower Eocene, NSB3/NTTe 6).

Sediments belonging to the topmost Tor and the Ekofisk, Vaale/Maureen, Lista and possibly Sele and Balder Formations, appear to have been blown clear of the immediate area during the impact event (based on the apparent absence of fossils that characterise these formations), with some of the ejecta flowing back into the area shortly afterwards (the 'mélange assemblages' of well 43/25-1). Lower Eocene (lower Ypresian) sediments are present in both wells but the pres-

ence of fossils restricted to the Late Paleocene in the 'mélange assemblages' of well 43/25-1 does not exclude the possibility that post-impact biological activity and deposition resumed during that time.

While this data does not support a direct link between the end-Cretaceous extinction event and the Silverpit Crater specifically, it does provide some support to the theory of bolide impact as the origin for the Crater and indicates a probable age for such an event.

The size of the impactor as suggested by STEWART and ALLEN (2005) is 170 metres in diameter. This is not a large impactor compared to, for example, the one that caused the Mexican end-Cretaceous Chicxulub Crater (estimated size c. 10 km diameter), but was large enough to create the Silverpit structure. The sequence of effects of such an impact in a shallow marine setting would be firstly to vaporise the water column, then as the impactor vapourised itself, to explosively excavate the seabed sediment, perhaps removing several hundred feet of deposits and disrupting the underlying formations. Initially, the impact would have left the crater area subaerially exposed as the force of the explosion pushed the sea back. However, almost immediately there would have been fall back of material thrown vertically, and a resurgence of the sea containing material expelled from the crater, and cannibalised sediment from the surrounding exposed seabed, back into the crater centre (see Fig. 5 - an impact



simulation model generated by Dr David CRAWFORD of the Sandia National Laboratory, USA). This is supported by the interpretation of the blocky texture of the 'top-Cretaceous level' in the central part of the structure (Zone 1) as a resurge deposit (STEWART & ALLEN, 2005). It is suggested above that the biostratigraphically mixed interval in the 43/25-1 well is supportive evidence to this interpretation.

The thin, mixed layer overlying the chalk was not observed in well 43/24-3 (c. 7 km from the point of impact). This would support the inference of STEWART and ALLEN (2005) that the impacting body was small, approximately 170 metres in diameter.

6. Future research

The location of the Silverpit structure makes future research difficult as it is dependent on expensive oil company or government/academic drilling operations, data and samples. Although a number of wells have been drilled in the general vicinity of Silverpit, they suffer from the same problem as the subject wells from this study: the targets were a Paleozoic reservoir and the Mesozoic-Tertiary section was regarded as overburden. Moreover, none (other than wells 43/24-3 and 43/25-1) have been drilled within the structural limits of the Silverpit Crater. However, some wells have been adequately sampled and this material is currently being examined to construct comparative stratigraphies in order to establish whether the large Lower Maastrichtian - Lower Eocene unconformity recorded in the 43/24-3 and 43/25-1 wells is unique only within the crater itself, or normal for the area around but outside of the structure.

In addition, such an event would cause 'collateral' damage in the form of seismic disturbances. Currently, evidence of these effects, including anomalous slumping and tsunami deposits, at or about the Paleocene/Eocene boundary is being researched (e.g., BIDGOOD, in prep.).

The possibility of finding an ejecta field in the geological record of the North Sea seems slender as the ejected materials were claystones and limestones, which would not have produced classic glassy tektites, or shocked quartz grains.

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