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DTI Strategic Environmental Assessment Area 4 (SEA4): Geological evolution Pilot Whale Diapirs and stability of the seabed habitat

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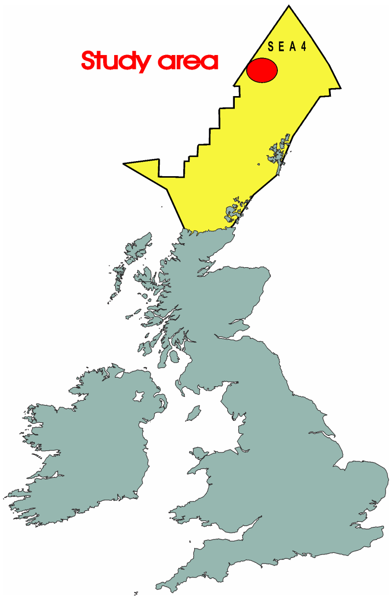

BRITISH GEOLOGICAL SURVEY

COMMERCIAL REPORT CR/03/082

DTI Strategic Environmental Assessment Area 4 (SEA4): Geological evolution Pilot Whale Diapirs and stability of the seabed habitat

R Holmes, P R N Hobbs, A B Leslie, I P Wilkinson, F J Gregory, J B Riding, R J Hoult, R M Cooper and S M Jones

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Foreword

This report is the product of a desk study by the British Geological Survey (BGS) in response to a contract from Geotek Ltd to report on the possible synergy between the geological evolution of the Pilot Whale Diapirs and the modern deep-water seabed sedimentary environment. The study area is in the Department of Trade and Industry Strategic Environmental Assessment area 4 (SEA4).

This report has been produced separately from two other reports which have been produced under the same contract for SEA 4:

1. BGS report CR/03/080 Subseabed geology
2. BGS report CR/03/081 Continental shelf sea-bed geology and processes

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Summary

The DTI 2002 programme of new deep-water seabed multibeam and sample data acquisition in SEA4 included surveys of a field of seabed mud mounds, collectively named the Pilot Whale Diapirs. The largest of these occur over a buried anticline and they are set in sediment debris flows that originated from grounded ice and submarine landslides. Other diapirs and mud mounds are sited on and adjacent to the north-east plunging Fugloy Ridge and buried transfer fault zones within a region subject to modern earthquakes. The focus of this study is on the SW group of the five main groups of large-scale mud diapirs with seabed elevation of 30m or more above the surrounding seabed and with very complex seabed geometries.

Diapiric sediment has been transferred to seabed from deep sources, in places from more than 500m below modern seabed and from strata more than 24 million years old. Interpretations of the fossil biota, sediment properties and seismic reflection profiles indicate that there is sub-metre scale heterogeneity in the composition and age of sediments cropping at or near seabed on the large-scale mud diapirs. Interpretations from the seismic reflection profiles and the fossil data from one site on the large-scale diapirs indicate that the large-scale mud diapirism post-dates approximately 5 million years ago and might have been initiated as late as 1.1 million years ago. The evidence suggests that rapid large-scale mud diapirism is not occurring at the present day. In contrast, interpretations of the regional geological setting and the sub-seabed data indicate that there are large areas with potential for modern, active and small-scale diapirism.

Reconnaissance sample surveys indicate that some of the steepest slopes on the large-scale diapirs are composed of rock and overlain by thin soft sediments with gravel at seabed. A numerical static stability model is presented that predicts the general conditions under which the modern seabed will become unstable on the large-scale diapirs. The model predicts that thin-skin seabed failures prevent thick accumulations of normally consolidated sediment on the steep flanks of the large-scale mud diapirs. These failures will contribute to the variability of the seabed substrates.

Contents

1 Introduction

Seabed mud mounds occur on the North Sea Fan between the Faroe-Shetland Channel and the Norwegian-Greenland Sea in the northern SEA4 area. The larger seabed mud mounds appear to have originated as sedimentary intrusions. They have ascended from deeply buried sediments and appear to have pierced both subseabed strata and seabed, forming diapirs. A small number of these diapirs have been previously described from reconnaissance seismic reflection surveys and have been named the Pilot Whale Diapirs (Haflidason *et al.* 1996). Data acquired since 1996 show that the Pilot Whale Diapirs occur as clusters or groups within a wider field of small mud diapirs and mud mounds (Figure 1).

The Pilot Whale Diapirs have intruded glacigenic debris flows. The youngest glacigenic debris flows are derived from rapid late Pleistocene sediment delivery to the North Sea Fan (Figure 1) at a time approximately >15Ka years ago when grounded glacier ice was in the Norwegian Channel (King et al, 1998). The tops of these glacigenic debris flows are exposed at seabed or are buried just below seabed and are associated with a gently undulating but otherwise planar muddy seabed. One of the environmental issues that arises in relation to the Pilot Whale Diapirs is that they provide examples of exceptionally variable seabed terrains that are set in the otherwise uniform deep-water basin. They also occur in the northern UK frontier hydrocarbons province and they are the largest diapirs preserved at seabed in the UK zone.

It is only relatively recently that large non-commercial regional datasets have been available for research on the Pilot Whale Diapirs. The research studies for this report have used extracts from data derived from systematic surveys of the whole of the northern SEA4. Thus the BGS single-channel airgun and pinger reflection seismic data have provided information for research on the sub-seabed formations (Brett, 2001; 2002), the DTI multibeam surveys have provided blanket seabed topographical and seabed textural information (Masson *et al.* 2002) and the DTI reconnaissance multicore and gravity core survey has provided seabed and sub-seabed geological samples (Leslie, 2002). The interpretations presented in this report are intended as a contribution to the ongoing research associated with the Pilot Whale Diapirs.

The focus of this study is on four groups of the large-scale diapirs with seabed elevation of approximately 30m or more above the surrounding seabed and informally referred to in this report as the NW, NE, SE and SW groups (Figures1, 2). The scope of this report is to interpret the geometry, geological setting, possible timing and seabed stability associated with the geological evolution of the NW, NE, SE and SW groups of diapirs and over a period ranging from approximately 35 million years ago to the present day. An overall scientific objective is to summarize how interpretations of sub-seabed geological processes may contribute to a better understanding of the origin and variety of the seabed and superficial sedimentary environments associated with the large-scale Pilot Whale Diapirs.

2 Interpretation of sub-seabed seismic facies

The glacigenic composite debris flows, the debris flows originating from submarine landslides, the diapirs and the mud mounds are characterised by internal facies of acoustic scatter and acoustic transparency on the sub-seabed seismic reflection profiles (Figure 3). These facies are interpreted as originating from sediments disturbed by historical or modern fluid or sediment mobilisation. The outcrop of these facies at seabed does not, however, provide diagnostic evidence for modern seabed instability. The sub-horizontal, layered acoustic facies are interpreted as evidence for relatively undisturbed sediments.

3 Geometry

An elevation of approximately 30m above the surrounding seabed has been chosen as an arbitrary boundary between 'large-' and 'small-' scale mud mounds and diapirs (Figures 1, 2). This has been chosen in an attempt to clarify the distributions of diapirs and mud mounds over their natural range of elevation above the surrounding seabed and which varies from less than 2m to more than 120m. The seabed distribution of the whole size range of diapirs and mud mounds is shown in (Figure 1).

The large-scale Pilot Whale Diapirs occur within a wider field of small mud diapirs and mud mounds. This 'wider field' is more or less 60 km in diameter (Figure 1) and it occurs in water depths varying from approximately 1450-1800m and on a seabed plateau with an average regional slope of approximately 0.3°.

The plan shapes of the largest seabed diapirs vary from isolated, almost circular, features to the complex diapir groups with irregular to rounded perimeters (Figures 1, 2). The SW group, for example, occurs with a ring-like enclosure of scarps ridges and mounds with an approximately 3km short diameter (Figure 2, A-C). Diapir crests rise to more than 120m above the surrounding seabed. Seabed slopes range from approximately 2° or less on the rises and crests to values of 35° or more on the flanks. The subtle changes of slope associated with the SW group (Figure 2, D) are presented as a typical example of the seabed geometrical complexity associated with the main groups of the Pilot Whale Diapirs.

4 Regional geological setting

The Pilot Whale Diapirs are set within packages of composite debris flows originating from glacigenic sources and one debris flow originating from the Miller Slide (Figures 1, 3). The topmost composite glacigenic debris flows extend as part of the North Sea Fan across the northern Faroe-Shetland Channel and into the Norwegian Greenland Sea. They partly surround the field of Pilot Whale Diapirs and also enclose individual diapirs. It is not always clear from the profile data if the glacigenic debris flows have been intruded by the diapirs or have flowed around them (Figure 3). It is also unclear from the profile data whether the debris flows from the Miller Slide (Long *et al.* in press) are intruded by the diapirs of the SW group (Figure 3, Profile B).

The Pilot Whale Diapirs occur over and adjacent to buried transfer faults and are adjacent to the epicentres of modern earthquakes (Figure 1). Although one modern earthquake plots to the trace of the Erlend Transfer Fault, the limited data for the distribution of all modern earthquakes since approximately 1973 indicate an apparent random distribution pattern in the SEA4 area (Hitchen *et al.* 2003). There is thus no secure basis for correlating the origin of the diapirs with natural seismicity. However, regional maps for the UK offshore are presented in Musson *et al.* (1997) and show that expected peak ground acceleration at seabed with annual probability of 10^{-3} is less than 0.05g and the corresponding value for 10^{-4} annual probability between 0.05 to 0.1g. Thus it is likely the peak ground accelerations may have contributed to the triggering of seabed instability on the diapirs (see section 6).

The 5 groups of the large-scale diapirs map to the axis and NW flank of a buried anticline of tectonically folded Palaeogene (>24Ma age) strata (Figures 1, 3). The anticline is defined by the deformation of top basalt (approximately 54Ma age) and the top Palaeogene Unconformity (approximately 24Ma minimum age) and is overlain by relatively undeformed sediments of Miocene (approximately 24-5Ma age), Pliocene (approximately 5-2.4Ma age) and Pleistocene to Holocene (approximately 2.4Ka –present-day) ages. Interpretations of the regional BGS profile data (unpublished) indicate that the anticline is plunging towards the NE. The timing of the seismic stratigraphic and tectonostratigraphic events listed above are summarised in Figure 4.

The overall depositional and structural geological setting summarised above for the large-scale Pilot Whale diapirs is comparable to that described by Hjelstuen *et al.* (1997) for the Vema Diapir Field, which is also situated in the Norwegian-Greenland Sea. Thus formation fluid overpressure is thought to have originated from sediment loading and density inversion. These diapirs were generated by the deposition of thick, rapidly deposited Pliocene-Pleistocene glacigene and other clastic sediments over weaker lower density, higher porosity, lower permeability diatomaceous Miocene and older sediments. The changes to the rates and the composition of sediment supply are identified with regional tectonic activity and global climate change since approximately 24 Ma (Figure 4) and were basin-wide over the North Sea Fan. Subsequently, the release of overpressured formation fluids was focussed over the anticline, where the overburden is thinner and weaker, and caused the diapirism.

Apparent reflector pull-down adjacent to the SW group of diapirs (Figure 3, Profile B) points to the possibility of local low compressional acoustic velocities originating from fluid (gas or liquid) ascent over the NW flank of the anticline. Alternatively, it can be argued that the process of sediment transfer that fed the ascent of the large diapirs could have caused formation sag and the appearance of reflector pull-down.

There are currently no sample data to correlate the distribution of the diapirs and sub-seabed acoustic scatter with biogenic or thermogenic gas- or other formation fluids. Further work is required to see if there is a relationship between the development of the Pilot Whale Diapir field and deep hydrocarbons seepages. For example, the diapirism may have been assisted by buoyancy associated with hydrocarbon escape from deeply-buried source rocks, above leaky transform faults (Figure 1), or above gaps in top basalt.

5 Timing and sources of diapirism

A study of the timing of the diapirism is relevant to understanding the seabed dynamics of the modern habitat. The sources of diapirism are important to understanding the potential variety of substrates that may be brought to seabed.

5.1 NW, NE AND SW DIAPIR GROUPS

The columnar sediment disturbances underpinning the groups of large Pilot Whale Diapirs are located over the flank of an anticline generated on folded Top Basalt and the Top Palaeogene Unconformity (Figures 1, 2). They are expanded to more than 500m below seabed on the flank of the anticline where they broach the Intra Neogene Unconformity (approximately 5Ma age) and Top Palaeogene Unconformity (approximately 24Ma age), but not Top Basalt (approximately 54Ma age) (Figure 3, Profiles A,B). The profile data showing the columns of disturbed sediments are interpreted to infer that pre Oligocene (>24Ma age) to Pleistocene (>10Ka age) strata have been incorporated into the diapirs. The similarities of the depths of disturbed sediments under the NW, NE and SW groups indicates that parts of these might have been sourced from an interval of similar sediment ages. Exceptions occur. For example, one profile across the SE flank of the NE group indicates that the potential for sourcing is limited to the interval extending from the seabed to the base of the composite debris flow packages (Figure 3, Profile A).

Sample sites +62 –02 20 (gravity core) and +62 –02 19 (multicore) were acquired on the flank of one of the SW group of diapirs (Figure 2 B-D; Figure 3 Profile B; Table 1).

BGS site registration number (SOC station number)	Sample recovery (m)	Location	Water depth (m)	Sample type
+62-02-19 (57064#1)	0.28	62° 38.76'N 01° 17.00'W	1515	Multi core
+62-02-20 (57064#5)	1.05	62° 38.71'N 01° 17.00'W	1515	Gravity core

Table 1. Diapir sample sites, SW Group

The interval between 0.87 m-0.99m below seabed at site +62 –02 20 consisted of unweathered, presumed diapir rock (Figure 4A) with dinoflagellate cyst and silicofossil assemblages restricted to age ranges in the Early-to-Mid Miocene (approximately 24-12Ma age range) (Figure 4).

The interval between 0.52-0.72m below seabed at site +62 –02 20 sampled weathered sediments (Figure 5A) that contained silicoflagellate marker taxa of Early Eocene (approximately 54Ma) to Early Miocene (approximately 16Ma) age ranges and diatoms indicating an Early Miocene (approximately 24-16Ma age) range (Figure 2). Some of the foraminiferida are restricted to the Oligocene (approximately 34-24Ma age) but foraminiferida restricted to the Pliocene to Pleistocene range (approximately 5Ma-10Ka age) are also abundant in the sample. The weathered interval 0.52-0.72m below seabed thus contains sediments that are both older and younger than the unweathered diapiric rock.

The interpretations of the biostratigraphical and seismic reflection data for ages of the sediments brought to seabed by the large-scale diapirs are thus consistent. The conclusions are that the deepest sources for the SW group were pre Oligocene (at least 35Ma age) and that shallow sediments occuring just under the seabed are sourced from strata that are currently buried to at least 500m below the present seabed (Figure 3).

The interval between 0.00-0.05m below seabed at site +62 –02 19 was acquired as an undisturbed seabed sample sited approximately 90m north of site +62-02 20 (Figures 2, 4A). There were no significant returns of taxa restricted to the pre-Pleistocene age (< approximately 2.4Ma) and the age ranges of taxa observed were consistent with the deposition of the seabed sample in a modern environment uncontaminated by reworked older sediments (Figure 4).

The anomalous range of taxa from the weathered interval at site +62 –02 20 are thus presumed to be derived from translated sediment following seabed failure (section 6) or have remained *in-situ* since diapiric emplacement. If the latter, then the composition of the diapiric sediment brought to seabed within the SW group is heterogeneous at the sub-metre scale and would provide a wide variety of cropping substrate lithologies and ages. This prediction is consistent with the interpretations of the seismic reflection profiles indicating the potential assimilation of a wide range of ages and types of sediment during the ascent of the large-scale diapirs.

On the basis of the structural and density inversion model (Hjuelston *et a.l*, 1997) and the biostratigraphical data summarised above, the SW group must post-date the Miocene folding of Palaeogene strata (<24Ma age), the deposition of Mid-Miocene taxa (<16Ma age) and probably post-dates the formation of the Intra Neogene (early Pliocene) Unconformity (< 5Ma age). As the Intra Neogene Unconformity and some of the packages of the composite glacigene debris flows are preserved below the elevation of the anticline crest it follows that the diapiric processes may have occurred prior to complete anticline burial (Figure 3). This speculation is important as it suggests that in conditions where the diapirism was principally driven by sediment-induced density inversion, the large-scale diapirs situated on the anticline flanks probably pre-dated those situated on the anticline crests. Further, it is suggested that the groups with the most recent gravity-driven diapirism are likely to be sited over the thinner and weaker overburden on the structural crest of the anticline. The NE and SE groups occur in this structural setting and the suggestion that these may be the youngest of the groups with large-scale diapirs is supported by the overall more rugged appearance of the seabed topography on these diapirs (Figure 2B).

The first glaciation supplying the debris flows to the Norwegian Channel was as early as 1.1 Ma (Sejrup *et al.* 1995) and possibly extended across the northern North Sea into the Faroe-Shetland Channel (Holmes, 1997). Thus, if triggered by sediment loading following the influx of the first thick glacigene debris flow packages to the North Sea Fan, the large-scale diapirism may be less than 1.1Ma age. If the abrupt change of composite debris flow package thickness across the SW Group (Figure 3, Profile B, X-X’) was caused by the group diverting the debris flow, then the data indicate that the large-scale diapirism was well established after 1.1 Ma.

It is suggested that the likely earliest age for large-scale diapirism in the SW group was post-Early Pliocene (<5 Ma) and that rapid sediment loading and gravity-driven diapirism was probably particularly active during the Pleistocene glacigene periods since approximately 1.1 Ma. It is further suggested that the lack of evidence for modern rapid and large-scale mud diapirism on the large-scale diapir groups may be due to the absence of rapid glacigene sedimentation since approximately 15Ka.

5.2 SMALL SCALE DIAPIRS AND MUD MOUNDS

Large areas of sub-seabed acoustic scatter underlie the ‘wider field’ of small diapirs and mud mounds on the NW flank of the anticline (Figure 3, NW section of profile A). If the areas of sub-seabed acoustic scatter are interpreted as sediments disturbed by fluids that originated during the process described by Hjelstuen *et al.* (1997), then the regional profile data (Figure 3) indicate that the fluids may been trapped under the shallow sub-seabed because of the lack of structural focussing to release fluid overpressures. Thus the ‘wider’ field of seabed inflation associated with the small seabed diapirs and mud mounds may be theoretically regarded as a diffuse, unfocussed, distribution pattern of regional seabed diapirism. The fields of shallow acoustic scatter may then be interpreted as indicators of fields of buried, partly suppressed, potentially slightly over-pressured, sub-seabed diapirism. These interpretations infer that the timing of the small-scale diapirism and mud mounds occurring over the shallow acoustic scatter is probably not tied to historical (glacigene) periods of high sedimentation rate. Areas of shallow sub-seabed acoustic scatter with seabed small diapirs and mud mounds can then be theoretically linked with areas with high potential for modern fluid escape and seabed instability. This is particularly useful as it can be adapted for a sampling strategy when prospecting for sites with modern cold seepages.

The Intra Neogene and Top Palaeogene Unconformities are more or less intact under the ‘wider‘ field of small seabed diapirs and mud mounds. The prediction is therefore that the small-scale seabed diapirs and mud mounds are composed of a less diverse and overall younger age range of seabed and superficial substrates compared those associated with the groups of the large-scale diapirs.

6 Static seabed stability model

Site +62 -02 20 (Table 1) is on the flank of a diapir on the SW group and at 0.87-0.99 m below seabed consisted of greenish, predominantly weak rock (shear strength range approximately >288 Kpa - <1.25 MPa) with a patchy sucrosic texture (Figure 5A). These properties are distinct from the very soft reddish brown muds in the overlying weathered interval (vane shear strength range 4.2-7.2 KPa, average vane shear strength 6 KPa) and from typical deep-water grey and brownish grey very soft and plastic North Sea muds at other sites, for example at site +62 -02 19 (vane shear strength range 3.6-5.2 KPa, average 4.4 KPa). More generally, vane shear strengths from 12 sites and sampled 0.20-0.8m below seabed in water depths 1450-1650m on the North Sea Fan range from approximately 2 to 6 KPa and average 4 KPa (Leslie, 2002). Sample sites +62 -02 20 and +62 -02 19 are gravelly at seabed (Leslie, 2002).

Sites 62-02 19 and 20 are on a diapir flank with typical seabed slopes of approximately 10-20° (Figure 2). Cohesive sediments measured with undrained shear strength less than 20 KPa, are classified as ‘very soft’ (BS5930:1999). According to a model for ‘infinite’ slope analysis (Prior and Suhayda, 1979), deposits of this shear strength and typical average bulk density 18.0 KN/m3 over an interval of 0.0-2.5m, are currently stable but would be unstable, subject to static forces, if found on seabed slopes of approximately >20°. If it is assumed that the ranges of unconsolidated sediment thickness, sediment shear strength and seabed slope that have discovered so far for the SW group are typical, then a numerical model can be constructed to show the boundary conditions for the sea bed stability of the large-scale diapirs (Figure 5B). It predicts that the large Pilot Whale Diapirs are prone to erosion by repeated thin-skin seabed failure over the range of approximately 5-35° slopes. The significance of this prediction is that it indicates another process for generating variations in the seabed substrates occurring on the large-scale diapirs.

The conditions modelled are on the boundary between static seabed stability and instability. Thus it would be expected from the return periods and magnitudes estimated for seabed ground accelerations (section 4) that modern earthquakes will contribute to modern dynamically-driven seabed instability on the diapir groups.

7 Conclusions

- The regional data indicate an origin for the N, NW, SW, NE and SE diapir groups from sub-seabed instability and vertical translation of sediment triggered by sediment loading over deeply buried positive structure.

- If sediment loading over buried positive structure is the dominant control on the large-scale diapir growth, then NE and SE groups are likely to be the youngest of the large-scale diapir groups.
- The largest diapirs have formed from sediments that have been intruded to seabed from 500m or more below seabed. During this process the diapirs have assimilated sediment from shallower sub-seabed and seabed formations.
- The diapiric process has generated significant sub-metre variations in the composition, hardness and age of diapiric sediments cropping at or near seabed on the large-scale mud diapirs.
- The oldest (weathered) rock recovered from one site on the the SW group is approximately 34 - 24 Ma age, the oldest (unweathered) rock approximately 24 - 11Ma age.
- The potential for variety in the composition and age of diapirc sediments cropping at or near seabed decreases with distance from the axis and upper flanks of the anticline.
- Samples indicate that the steeper flanks of the largest diapirs consist of gravelly muddy sediments at seabed that are underpinned by thin layers of unconsolidated sediments resting on weak rock.
- A quantitative static stability model predicts that the seabed is unstable on the large-scale diapirs over a wide range of unconsolidated sediment thicknesses up to approximately 2m and seabed at angles up to 30° or more.
- Thin-skin (small-scale) sediment instability is predicted as a factor with the potential to prevent thick sediment accumulation of the diapirs. This form of instability is one other process that has exposed a wide variety of rock formations at seabed and just below seabed.
- A likely ealiest age for the large-scale diapirism in the SW group was Early Pliocene (5Ma age) or thereabouts. Components of sediment loading and gravity-driven diapirism probably continued through the major glaicigene periods of the Pleistocene since approximately 1.1 Ma.
- Modern diapiric activity and fluid escape at seabed is most likely to occur within the diffuse field of small scale diapirs and mud mounds and where they are underlain by shallow acoustic scatter.
- Modern earthquakes are a likely cause of some modern instability on the large-scale diapirs.

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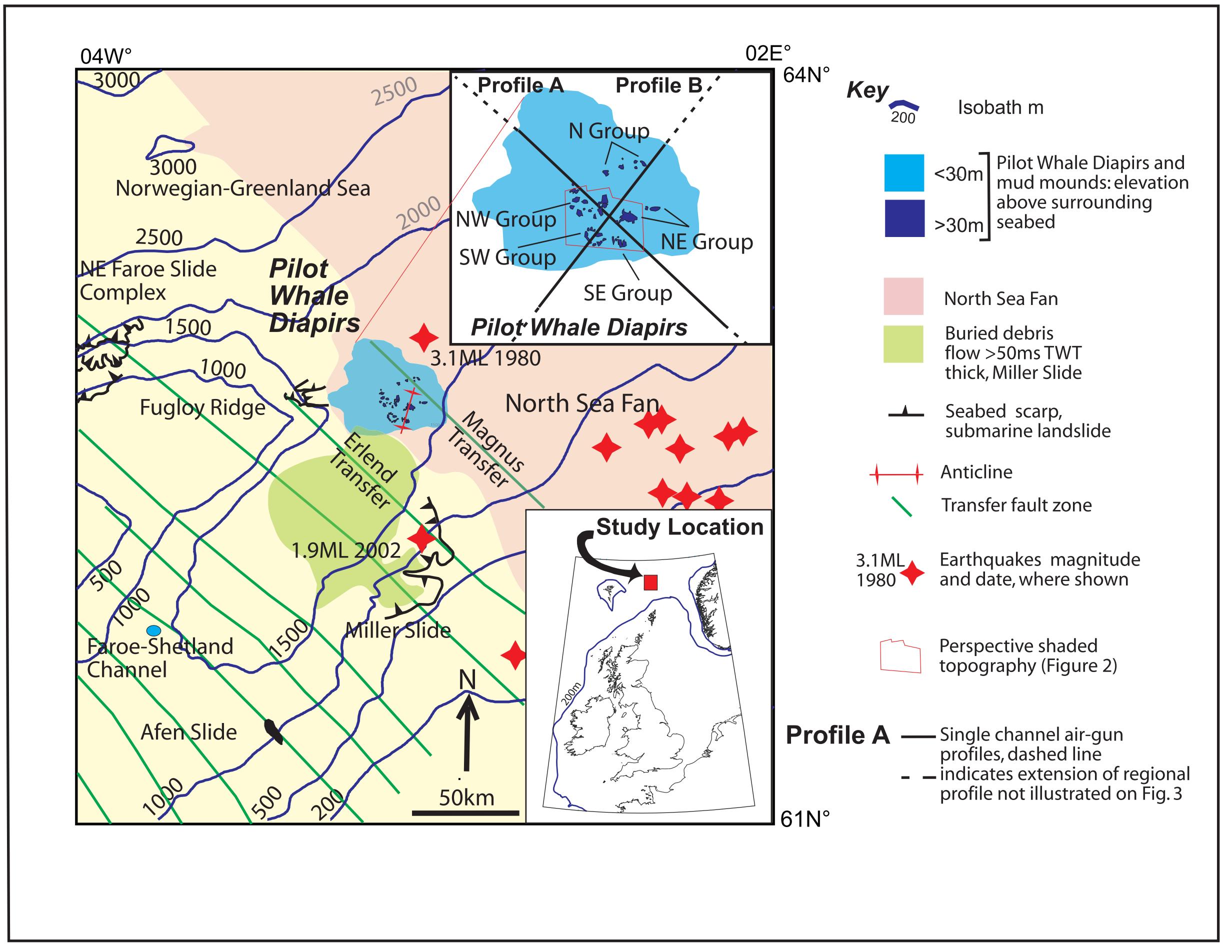


Figure 1 Location and geological setting Pilot Whale Diapirs

North Sea Fan defined by near-seabed glacigenic debris flows, modified after Taylor et al. (2003); NE Faroe Slide Complex after van Weering et al. (1998); slides on Fugloy Ridge adjacent to Pilot Whale Diapirs after Masson et al. (2003); Miller Slide after Long et al.(in press); Transfer (fault) zones after Rumph et al. (1993); earthquake data from the BGS database of natural seismicity. The extents of large-scale diapirs >30m elevation and smaller-scale diapirs and mud mounds<30m elevation mapped from intepretations of DTI multibeam data acquired in SEA4, 2002 and interpretations of BGS pinger acquired since 2001(Brett, 2001, 2002).

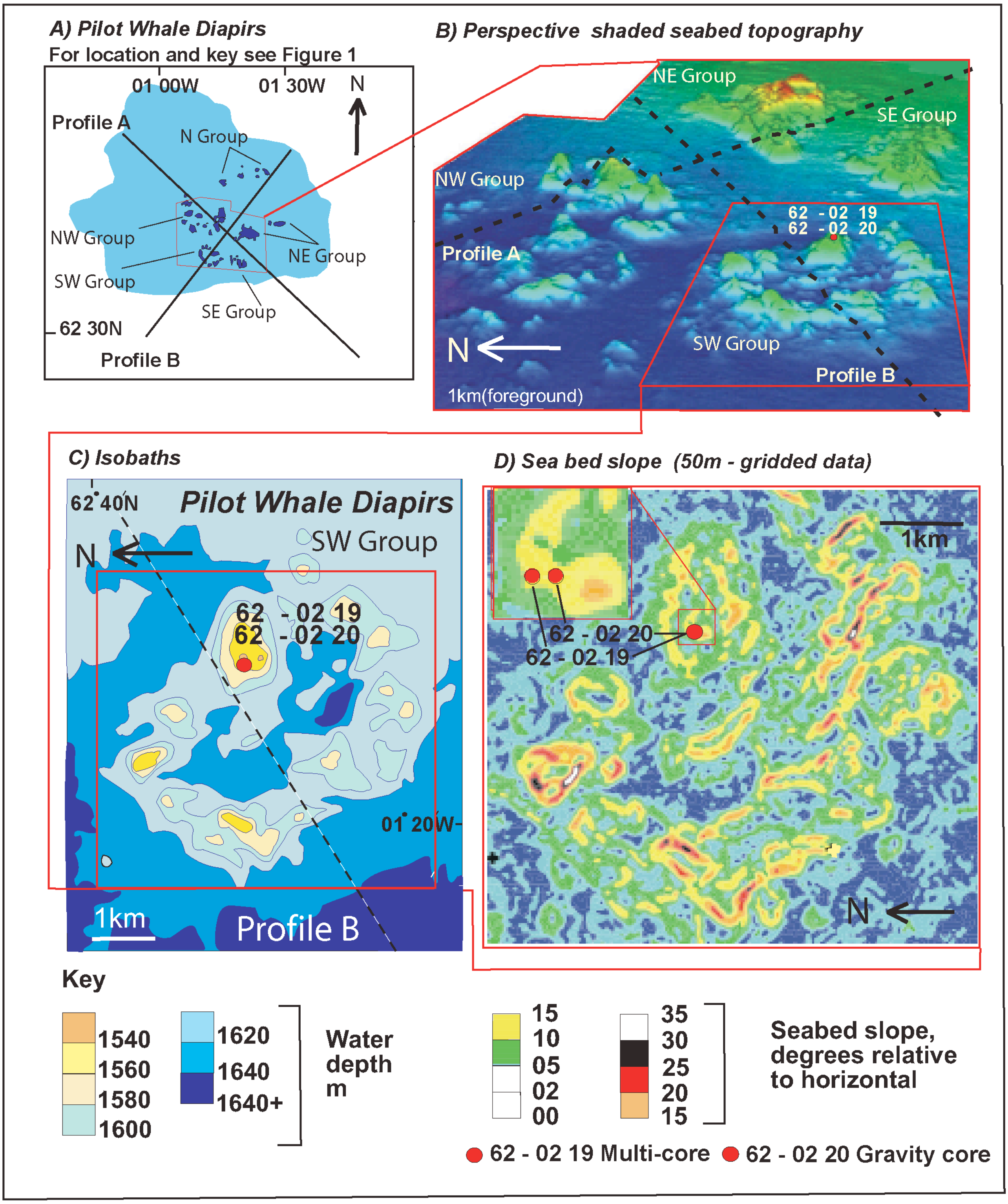
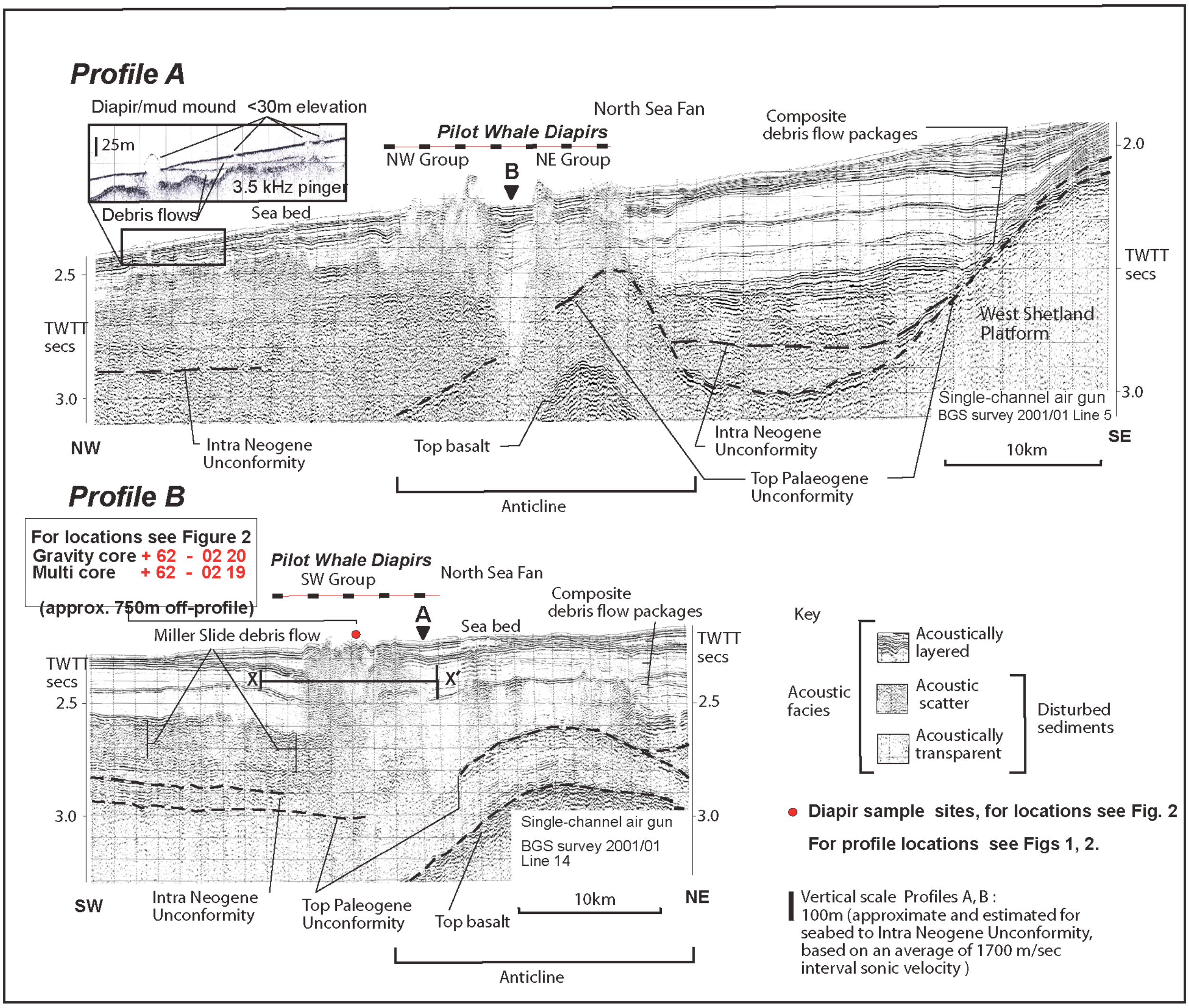


Figure 2 Geomorphology and sample sites


Profile A

Single-channel air gun
BGS survey 2001/01 Line 5

Profile B

For locations see Figure 2
Gravity core + 62 - 02 20
Multi core + 62 - 02 19
(approx. 750m off-profile)

Single-channel air gun
BGS survey 2001/01
Line 14

● Diapir sample sites, for locations see Fig. 2

For profile locations see Figs 1, 2.

Vertical scale Profiles A, B :
100m (approximate and estimated for seabed to Intra Neogene Unconformity, based on an average of 1700 m/sec interval sonic velocity)

Figure 3 Seismic reflection profiles

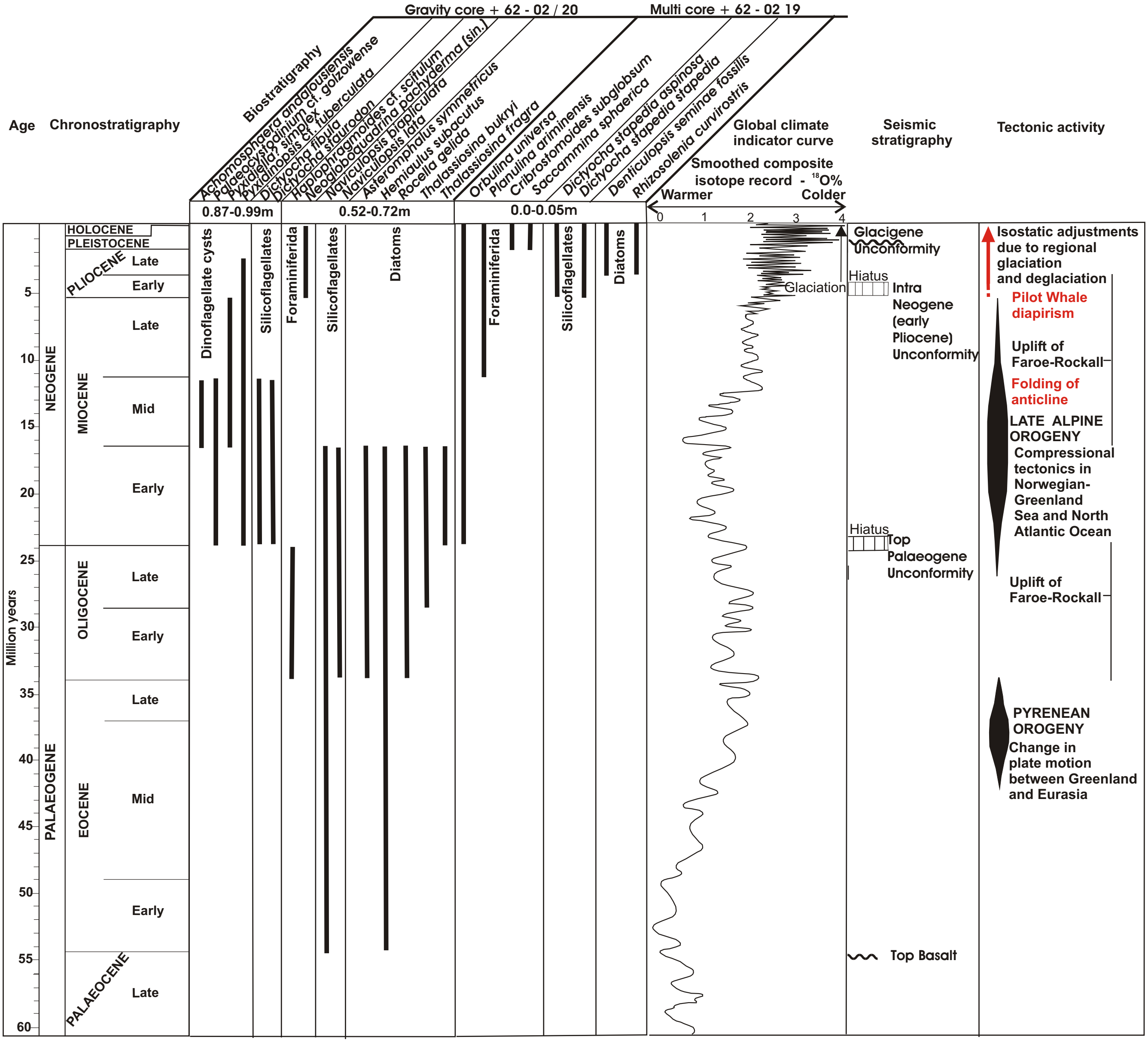


Figure 4 SW DiapirGroup: seabed and near-seabed ages, seismic stratigraphy, tectonostratigraph, global climate change

Chronostratigraphy after Bergrenn *et al.* (1995); climate curve based on oxygen isotope ranges in Atlantic waters, after Abreu and Anderson (1998); tectonic activity and regional unconformities adapted after Stoker *et al.* (2002) and STRATAGEM partners (2002, 2003); hiatus interval times associated with unconformities insecurely locally dated and not to scale. Full lists of taxa, many not illustrated this figure, age ranges, counts per sample are available from the BGS.

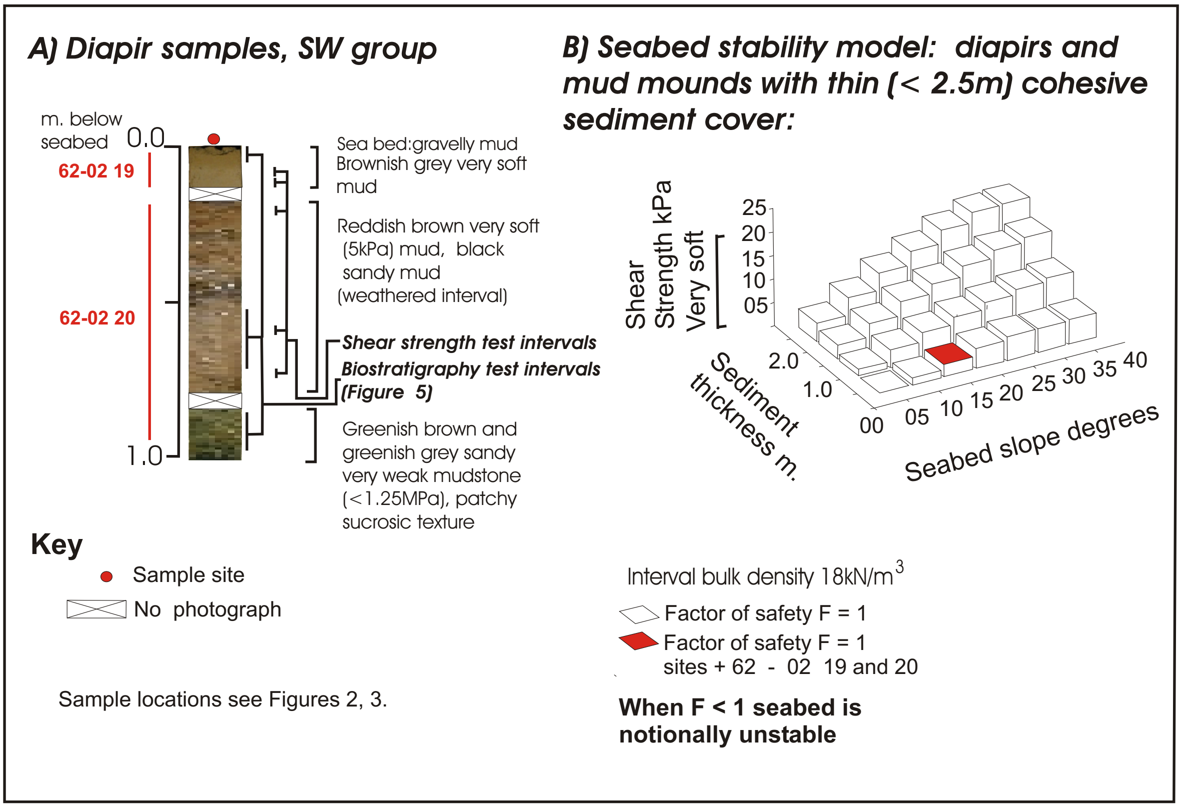


Figure 5 SW diapir group: sample logs and notional seabed stability model