

P. Van Rensbergen · A. Rabaute · A. Colpaert
T. St. Ghislain · M. Mathijs · A. Bruggeman

Fluid migration and fluid seepage in the Connemara Field, Porcupine Basin interpreted from industrial 3D seismic and well data combined with high-resolution site survey data

Received: 1 January 2004 / Accepted: 22 June 2005 / Published online: 18 November 2005
© Springer-Verlag 2005

Abstract This study documents the suite of processes associated with source-to-seafloor fluid migration in the Connemara field area on the basis of 3D seismic data, well logs, 2D high-resolution seismic profiles, subbottom profiles, short cores and sidescan sonar data. The combination of datasets yields details about fluid migration pathways in the deep subsurface, in the unlithified shallow subsurface and about the distribution of fluid and gas seeps (pockmarks) at the sea floor. The Connemara field area is characterized by vertical fluid migration pathways (“seismic chimneys” or “gas chimneys”) that extend from the top of the Jurassic sequence, cross-cutting the entire Cretaceous sequence to the Upper Tertiary deposits over a vertical distance of up to 1.5 km. Their localization is mainly structurally controlled to the crest of tilted fault blocks along the main hydrocarbon migration pathways. These chimneys are important conduits for focused vertical fluid/gas flow from the deep to the shallow subsurface. However, gas seeps (pockmarks) at the sea floor are almost randomly distributed, which indicates a change from focused to diffuse fluid/gas migration in shallow, unconsolidated sediment. Where the vertical chimneys reach up to unlithified Eocene to Miocene sands, widespread deformation, interpreted as fluidization, occurs around the main conduit. This deformation affects about 32% of the entire unconsolidated Tertiary section (Late Eocene – Miocene). A Plio-Pleistocene glaciomarine drift with up to five horizons with iceberg ploughmarks seals the

Tertiary sands. In the near surface sediments it is observed that gas accumulation occurs preferentially at iceberg ploughmarks. It is inferred that lateral migration at five levels of randomly oriented ploughmarks dispersed gas over larger areas and caused random pockmark distribution at the sea floor, independent from the underlying focused migration pathways. This study demonstrates that fluid flow migration changes from structurally controlled focused flow in the deep consolidated subsurface to diffuse flow, controlled by sediment variability, in the shallow subsurface. This result is relevant to a better understanding of the distribution of seepage-induced features at the seafloor related to focused hydrocarbon migration pathways known from industry data and fluid flow modeling.

Introduction

The study of submarine hydrocarbon seeps attracts much attention because of the specific micro-environment they create at the sea floor, characterized by specialized bacterial activity, mineral precipitation, typical benthic faunal associations and for their effect on water column dynamics. The occurrence and distribution of seeps is most often attributed to focused migration pathways along outcropping permeable beds and faults. Possible fluid flow conduits in the subsurface observed on basin-scale seismic data or obtained from fluid flow modeling based on such data are considered direct feeder systems to sea floor seeps and a correlation between them is often sought. The Connemara field area is characterized by vertical fluid migration pathways (“seismic chimneys” or “gas chimneys”) that extend from the top of the Jurassic sequence, cross-cutting the entire Cretaceous sequence to the Upper Tertiary deposits over a vertical distance of up to 1.5 km. These vertical chimneys indicate important pathways of fluid and gas migration from the deep subsurface to the shallow subsurface and seemingly to the sea floor. This paper documents the suite of processes associated with

P. V. Rensbergen (✉) · A. Colpaert · T. St. Ghislain
M. Mathijs · A. Bruggeman
Renard Centre of Marine Geology, Universiteit Gent,
Krijgslaan 281-S8, 9000 Gent, Belgium
E-mail: pieter_vanrensbergen@yahoo.com
Tel.: +32-9-2644590
Fax: +32-9-2644967

A. Rabaute
CEREGE, Marseille, France

A. Colpaert
Tromsø, Norway

source-to-surface fluid migration on the basis of 3D seismic data, well logs, 2D high-resolution seismic profiles, subbottom profiles, short cores and sidescan sonar data. It is found that fluid flow patterns change drastically in the shallow subsurface from focused to diffuse flow, which leads to an almost random pockmark distribution at the sea floor. Hence, there is no direct relationship between the localization of subsurface conduits and sea floor seeps. Instead, vertical and lateral changes in sediment properties in the unconsolidated, unfaulted shallow subsurface control seep occurrence and distribution. This observation is important to interpret seepage-induced features at the seafloor in relation to the underlying geology. Dispersion of hydrocarbon gases over larger areas likely reduces activity, intensity and life-span of a single seep and thus limits the magnitude of associated biological, geochemical and oceanographic effects.

Setting of the study area

The Connemara field area is situated at the northern end of the Main Porcupine Basin (Fig. 1). The main stratigraphic division of the Porcupine Basin is recognized in the southern part of the study area: a Paleozoic pre-rift, a Mesozoic syn-rift succession, and a Cenozoic post-rift succession (Ziegler 1982, Croker and Shannon 1987, Shannon 1991—Fig. 2). Middle to Upper Jurassic rocks rest unconformably on Permo-Carboniferous rocks and were deposited in NE–SW-oriented rifts, characterized by block faulting and divergent reflection patterns. Active rifting ended in the Late Jurassic. The post-rift sequence consists of Cretaceous clays, siltstones and sandstones deposited as a prograding wedge from the North into the subsiding post-rift basin. Chalk occurs only at the top Albian. The Tertiary sequence consists of lithified (Early Eocene) to unlithified (Eocene – Oligocene – Miocene) sandstones deposited in coastal to open marine environments. The youngest sequence (probably Plio-Pleistocene) consists mainly of a glaciomarine drift with several levels of iceberg scour marks. The northern part of the study area is dominated by a large horst block that consists of inverted Jurassic syn-rift sediments and the Cretaceous post-rift section is thin or missing. This main structural division is smoothed by the Late Cretaceous unconformity and is not reflected in the overlying

Tertiary–Quaternary sequence. The inverted horst block corresponds to the northern termination of the Main Porcupine basin (Moore and Shannon 1995). On general structural maps, the horst block is indicated as an E–W trending high but in detail its structure is more complex and appears to consist of different structural highs along N–S to NE–SW faults, probably inherited from the Mesozoic rifting phase. Most of the faults occur within the syn-rift succession and only a few faults remained active throughout the post-rift phase. All faults terminate within the Tertiary section and no active faults were observed within the Plio-Pleistocene glacio-marine drift or at the sea floor. The main hydrocarbon sources in the area are Middle Jurassic bituminous rocks at burial depths exceeding 2.2 km. Hydrocarbon production started from the Late Cretaceous onwards in the deeper parts of the basin and is probably continuing today (MacDonald et al. 1987). No mature source rocks are thought to occur within the Connemara field area.

Available data

The available data for this study consist of:

- A 3D seismic survey provided by Statoil Ireland Ltd. This data volume (ST9605) was acquired by Geco-Prakla in 1996 and covers a surface area of 380 km² at the northern end of the main Porcupine basin. It is a rectangular survey area with a SW–NE orientation covering part of Ireland's offshore license blocks 26/28 and 26/29.
- Well logs from five exploration wells in this area were provided for this study by the Petroleum Affairs Division in Dublin. The details are given in the Table 1.
- Site survey data in the southern half of the study area were provided by Statoil Ireland Ltd. and consist of 27 high-resolution 2D seismic profiles, 27 subbottom profiles, 25 sidescan sonar profiles and 13 shallow geotechnical boreholes. Two additional high-resolution seismic lines over the area were acquired by the RCMG.

Data description and interpretation

This section is divided into three parts: the deep subsurface, the shallow unconsolidated subsurface and the sea floor. The deep subsurface consists of Carboniferous to Early Eocene sedimentary rocks from depth up to 800 m. It is described on the basis of 3D seismic data and correlated well logs. The shallow subsurface consists of unlithified Eocene to recent sediments from a depth of about 800 m upwards. There is almost no well log information and it is described on the basis of 3D seismic data and 2D high-resolution seismic lines. The uppermost part has been studied using 3.5 kHz subbottom profiles and a few cores while sidescan sonar mosaic images the sea floor in part of the study area.

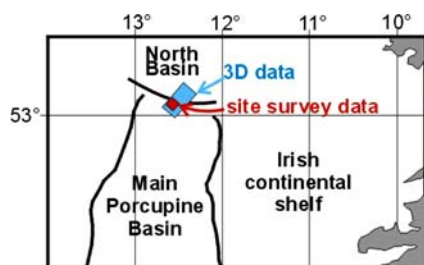


Fig. 1 Location of the study area in the northern part of the Porcupine Basin, offshore Ireland

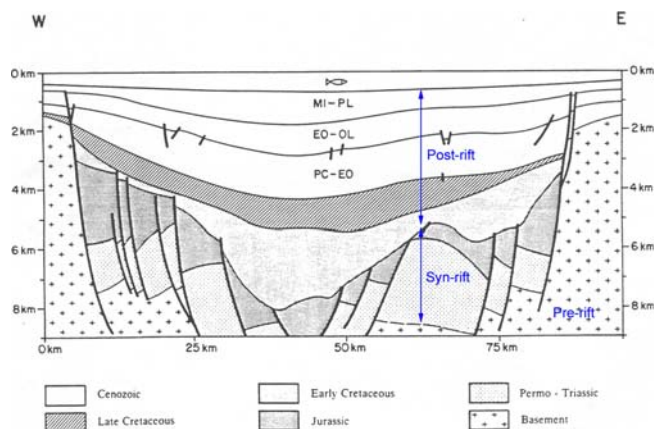


Fig. 2 General E–W cross section of the Porcupine Basin (modified from Ziegler 1982)

Deep subsurface: 3D seismic characterization of vertical fluid migration pathways in relation to the structural style

Seismic chimneys are vertical columnar zones of chaotic reflections that disrupt the depositional layering (Fig. 3). They reach up from the Top Jurassic (Fig. 4) to within the Tertiary section and occasionally reach the Quaternary–Tertiary glaciomarine drift. In places where the Jurassic sequence occurs at large depths, they form isolated chimneys, over 1.5 km tall, and between 200 and 600 m in diameter. Large isolated chimneys occur at the top of Jurassic rift shoulders where the Cretaceous mud rock sequence is several 100 m's thick. The chimneys are associated with large normal faults that are the upward extension of Jurassic boundary faults. The location of the chimneys is probably controlled by the localization of the closure of Jurassic reservoir rock at the crest of the fault blocks and the updip termination against the large boundary faults. The chimneys occur in association with these faults, both in the hanging wall and the footwall, and do not follow the listric fault path. On the horst blocks where the top of the Jurassic sequence is shallow and the Cretaceous mud rocks are almost entirely missing, they occur in dense clusters (Figs. 5, 6) and it is sometimes difficult to distinguish individual chimneys.

The chimneys become clearly visible in the stratigraphy from the base of the Albian massive sandstones (orange reflector), which is underlain by a thick layer of mudstones of lower Cretaceous age (Barremian, Aptian) characterized by prograding clinoforms. The sandstones and the mudstones show typical physical

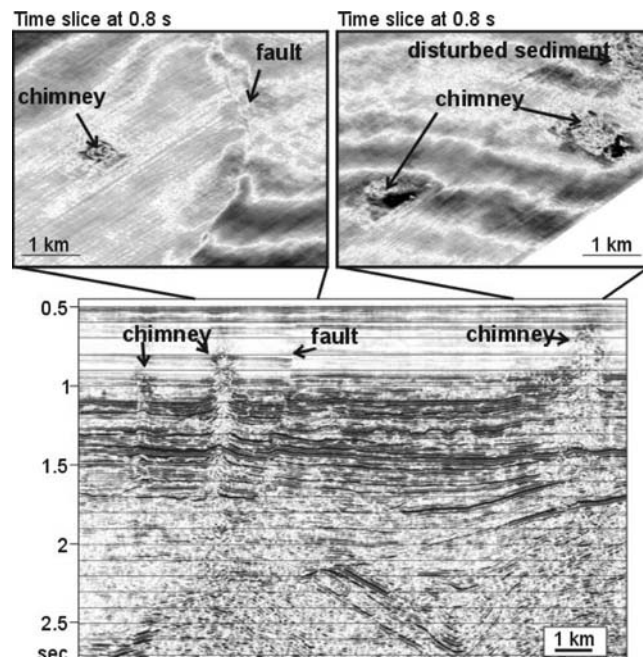


Fig. 3 Vertical seismic section (*bottom*) shows three vertical seismic chimneys that reach up from the top Jurassic to unlithified Tertiary deposits. Time slices at 0.8 s (*top*) show that chimneys are semi-circular anomalies in a horizontal plane. See Fig. 4 for stratigraphic interpretation

properties, such as low and high gamma-ray, respectively (Fig. 7; measured values are given in Appendices 1 and 2). They have similar compressional acoustic velocities ($\sim 2,700$ m/s), indicating that the mudstone formation is extremely tight and compacted, which is confirmed by the high resistivity (2.1–2.8 Ω m). The low resistivity of the Albian sandstones (0.8–0.9 Ω m) indicates that they are water-bearing, while the low gamma-ray indicates that they are relatively clean (i.e. the clay content is low), and we can thus trust the neutron porosity log (well 26/28-1), which indicates 34% porosity (see Appendix 1). These characteristics together with a normal acoustic compressional velocity indicate that the Albian sandstones are lithified, but still have sufficient connected porosity to allow fluid to migrate through them. Within the Cretaceous mudstones, chimneys are visible as disrupted and/or subdued reflections, but there is no indication of updoming or characteristic amplitude effects that often mark the path of vertical fluid injections. From the base of the Albian sandstone upwards, they consist of a core with a chaotic seismic facies that disrupts the stratification (Fig. 8). Reflections are disrupted and uplifted around the chaotic core of the chimney (facies 1). On the

Table 1 The available wells for this study (Petroleum Affairs Division)

Well	X-coordinate (UTM)	Y-coordinate (UTM)	Total depth (m TVD)	Year
26/28-1	663666,31	5879791,50	3315	1979
26/28-2	662226,81	5879653,00	2697	1980
26/28-3	665882,30	5883140,40	2588	1981
26/28-4a	670052,12	5883584,74	2418	1981
26/28-5	664123,00	5878928,97	2810	1984

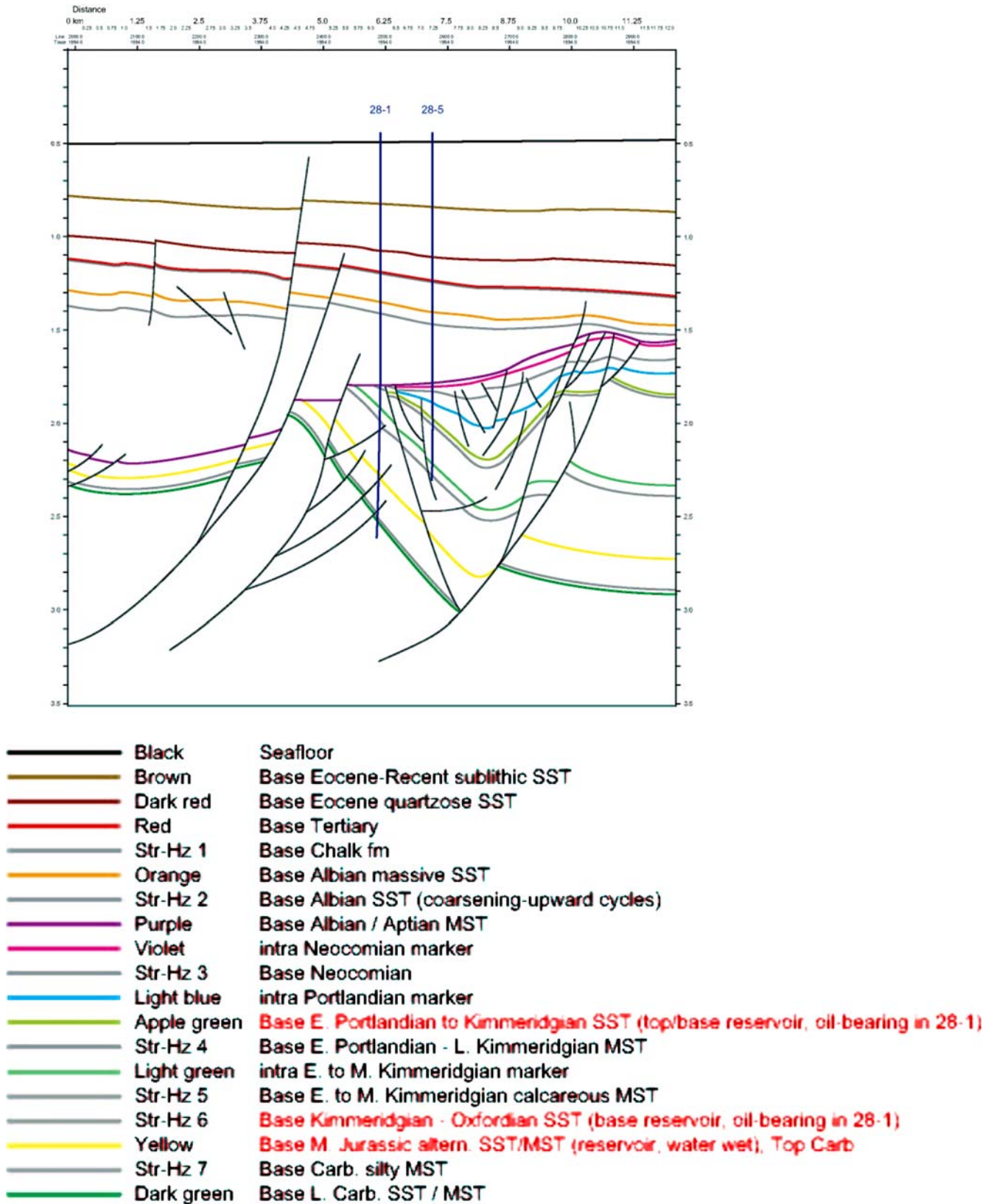


Fig. 4 Stratigraphic interpretation of the seismic section based on correlation of well logs (see well log data in Appendices 1 and 2)

seismic profiles, it seems that the Albian sandstones, contrary to the overlying Tertiary deposits, are little disturbed by the migrating fluids, maybe due to the very coherent nature of these deposits. The top of the Albian sandstone reservoir is clearly disrupted and displaced at the larger vertical chimneys, although no amplitude effects are visible.

In the Tertiary section the sediment disturbance becomes significant on seismic data. The Tertiary deposits start with a mudstone deposit of Paleocene age. Its properties are more that of a siltstone (low gamma-ray). From well 26/28-1 and 26/28-3, that is to the top of the horst block, we document a decrease in resistivity and a sharp drop in acoustic velocity. This may indicate that this layer is less compacted at the top of the horst, allowing the fluids to break through more easily. The Paleocene mudstones are overlain by Eocene sandstones, firstly as a lithified layer (up to the brown reflector), and then as a sub-lithified deposit, with a slow decrease in acoustic velocity. Within the Early Eocene sandstone the chimney changes gradually from dis-

rupted reflections with chaotic core (Fig. 8, facies 1) to updomed continuous reflections with enhanced amplitude without a chaotic core (Fig. 8, facies 2). Smaller chimney-like structures occur up-dip from larger chimneys and seem to root within Early Eocene sandstones. This indicates a degree of lateral migration within the Early Eocene sandstones. In the unlithified sediments, the degree of uplift and the width of the chimney gradually decreases until only lateral amplitude effects remain without visible updoming or disruption of the reflections.

Interpretation

The chimneys are interpreted as vertical injection pathways of overpressured fluids. In rocks, fluid injection occurs along vertically propagating hydrofractures initiated from an overpressured reservoir when pore fluid pressures rise above the minimal horizontal stress plus rock strength (Engelder and Leftwich 1997). The mechanism of fracture propagation (and overpressure

Fig. 5 Distribution of seismic chimneys on top of the Base Tertiary time-structure surface. Chimney clusters occur at the footwall of shallow fault blocks. Isolated chimneys occur in the basins. Different clusters are indicated by numbers

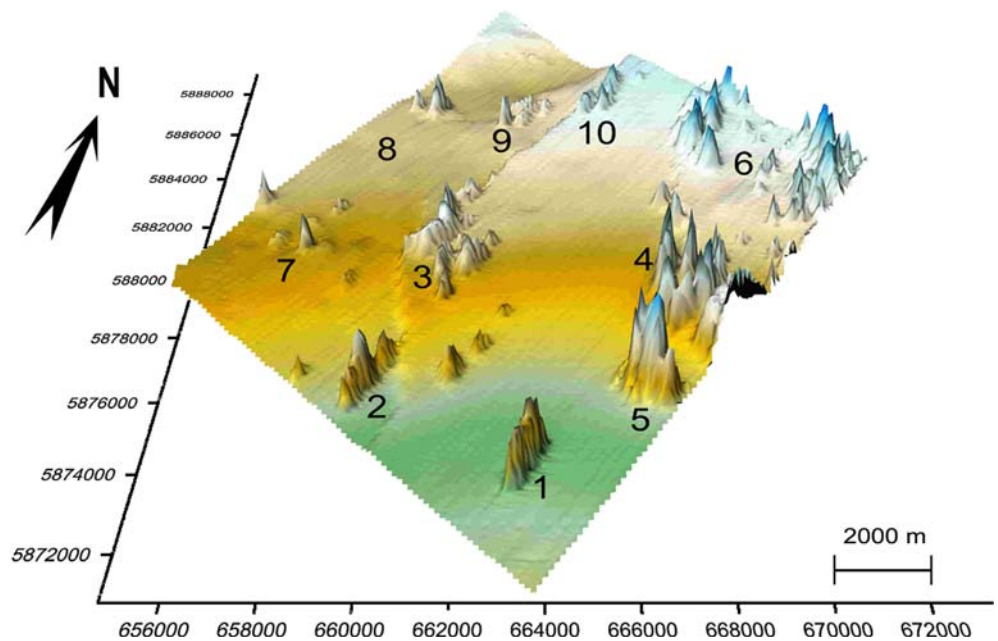


Fig. 6 Simplified sketch of the occurrence of seismic chimneys in relation to the basin structure

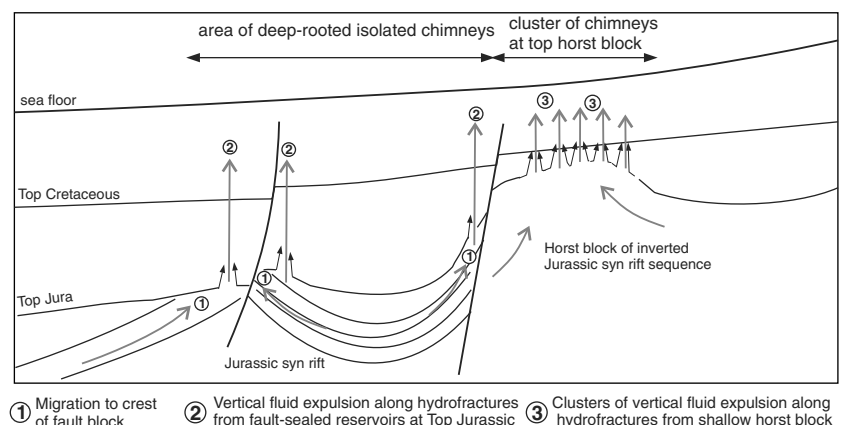
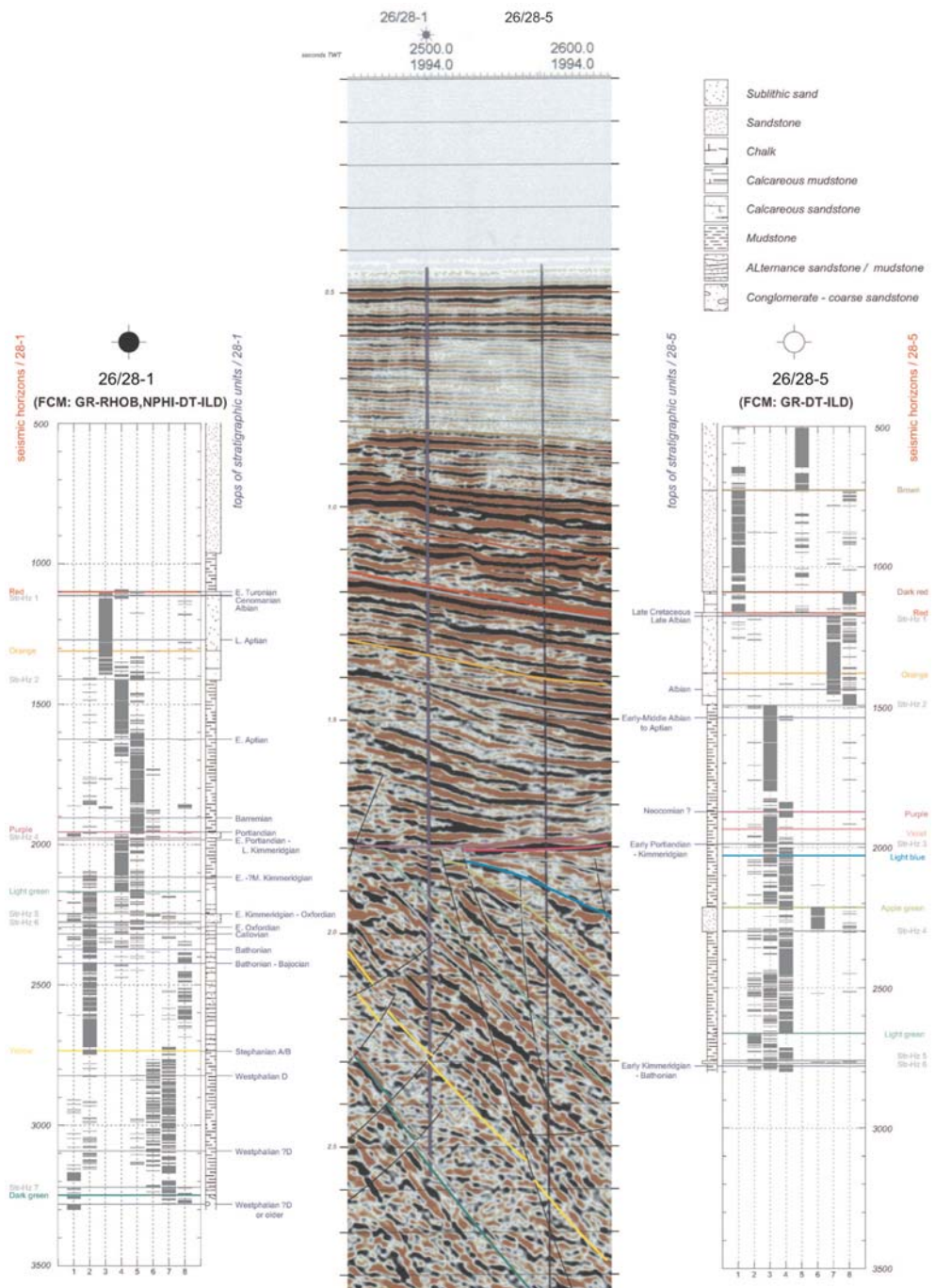


Fig. 7 Well log interpretation and correlation of wells 26/28-1 and 26/28-5; see Appendices 1 and 2 for data



preservation), especially through permeable rock (in this case Albian sandstone) is still debated. In tight mud rocks, vertical fluid injection may be enough to propagate pore fluid overpressure and maintain the pressure drive. In more shallow and more permeable conditions, gas ebullition and expansion from the ascending fluids may be an additional source of overpressure. It was also suggested by Van Rensbergen et al. (1999) that vertical gas migration precedes fracture formation, locally increases pore fluid pressures and facilitates fracture formation by vertical injection. In porous rocks, diagenetic cementation may create pressure compartments that

hinder lateral leakage and pressure drops. Alternatively, Revil (2002) suggests that propagation of the fracture shock wave creates a vertical fluid expulsion pathway. Nevertheless, there seems to be agreement that chimneys are important pathways for vertical fluid and gas migration (Heggland 1997), as is in this case confirmed by the large-scale fluidization structures in unlithified sands (see next section). The larger chimneys display typical characteristics of updoming reflections around a chaotic core. Van Rensbergen et al. (1999) proposed that updoming reflections around the vertical intrusion occur at relatively shallow burial depths. At greater

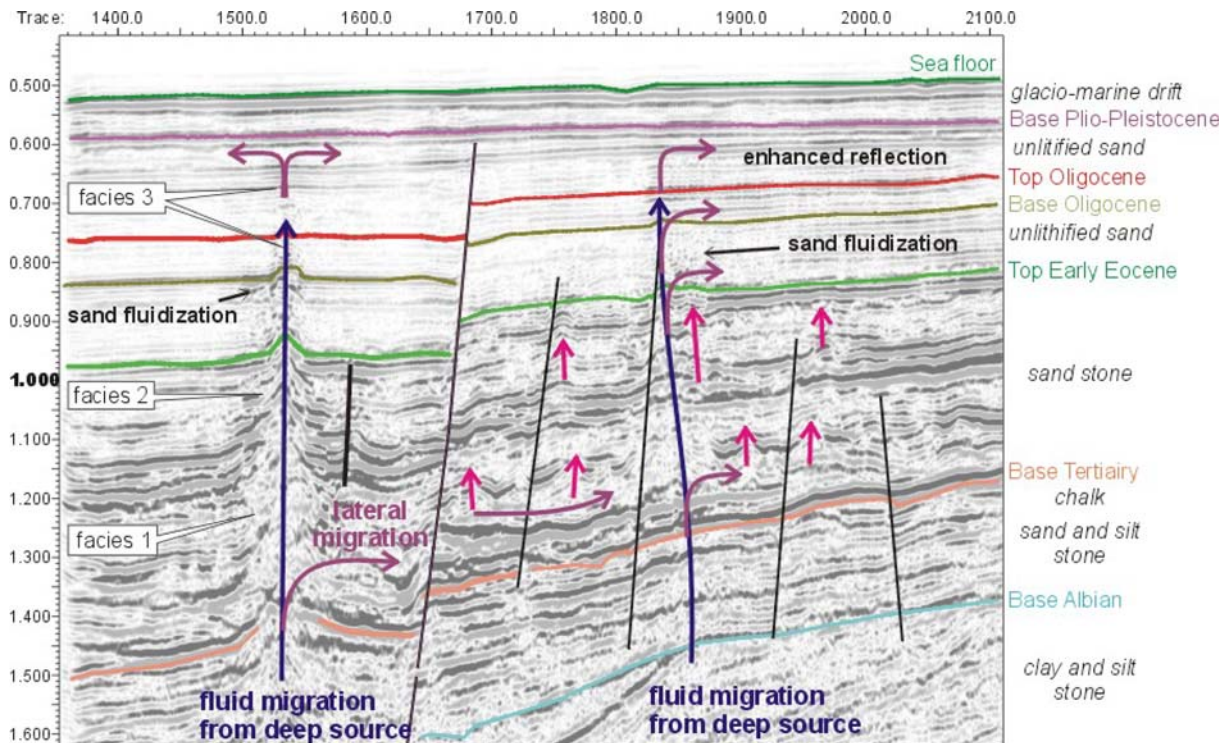


Fig. 8 Sketch of fluid migration pathways based on seismic and well log interpretation. Deep-rooted vertical chimneys are main conduits for vertical fluid migration from Jurassic reservoirs. Where the chimneys cross permeable layers (Early Eocene), lateral fluid migration occurs along dipping strata. Secondary chimneys root in the Early Eocene layer. In the younger unlithified sands fluid injection causes wide-spread deformation—interpreted as fluidization—and pockets of gas charged sediment (seen as enhanced reflections)

depths, the weight of the overburden impedes uplift of the overburden strata and brecciation will mainly occur. After brecciation, rock clasts can be transported vertically upward along with the fluid flow (Lewis and Byrne 1996). The size of the chimney decreases rapidly in the unlithified shallow subsurface but the lateral extent of the sediment deformation is seen to increase in unconsolidated sand layers.

The origin of the overpressure is, in this case, attributed to the accumulation of hydrocarbon fluids that migrated northwards from mature source rocks into Middle Jurassic reservoir sandstones and claystones. Hydrocarbons accumulated at traps at the Upper Jurassic/Cretaceous unconformity, at the crest of fault blocks and mainly at the crest of the uplifted horst. Subeconomic oil and gas reservoirs were found in the Jurassic sequence at wells 26/28-1 and 26/28-2 while gas and oil shows were found in well 26/28-3. The Early Cretaceous sequence constitutes a thick, tight fine-grained seal in most of the study area but is completely missing at the crests of the horst blocks. Here, Jurassic continental deposits are overlain by Cretaceous coastal sands separated from Eocene sands by moderately compacted Paleocene clay or siltstone. The crest of the horst block is a very leaky trap and fluid injection features are abundant. Pore fluid pressures can rise by lateral flow towards the crest of the horst block and exceed the minimal principal stress in the overlying Paleocene seal (Stump and Flemings 2000; Boehm and

Moore 2002). Where the tops of the fault blocks occur at deeper levels the Paleocene and Cretaceous seals become more effective. Fluid injection becomes less abundant and occurs as tall isolated chimneys, originating both at the hanging wall and footwall side of large syn-rift faults. It is interpreted that these faults are lateral seals for dipping reservoir strata at the flanks of the syn-rift section.

Several smaller chimneys appear to root in the Eocene section, up dip from large, deep-rooted chimneys, and appear not to be connected to deeper Jurassic reservoirs. This suggests that important lateral fluid flow occurred within the Eocene sandstones, which created smaller chimneys updip from large deep-rooted structures.

Shallow subsurface: sand fluidization structures in unlithified Late Tertiary sands based on 3D seismic data

Within shallow unlithified sediments (Late Eocene–Miocene), the chimneys are apparent mainly as vertical stacked zones of enhanced reflectivity. At clay layers, updoming and disruption of reflections is visible, while in unlithified sand layers, disturbed, discontinuous, hummocky stratification with high amplitude patches adjacent to the seismic chimneys contrasts to its overall low-amplitude parallel seismic facies. This facies change is interpreted as deformation of cohesionless, unlithified sands, caused by lateral fluid

injection. V-shaped bright spots occur at the level of sealing clay layers and probably represent injection structures where pore fluids break through the top seal (e.g. MacLeod et al. 1999). Abrupt lateral amplitude increases occur at the Top Oligocene reflection (Fig. 9) and similarly at the Top Early Eocene reflection. Their down-dip limit is sharp and, although the horizons are almost 200 ms apart, almost at the same location. Their up-dip extent is large with a gradual facies change to unaffected sand layers. This amplitude contrast may indicate gas-charged sediment (probably without fluidization), or alternatively, it may be due to interference caused by lateral injected sediment or outflow deposits. Although zones of enhanced reflectivity appear to reach up to the sea floor, a detailed study of the shallow subsurface shows this is in fact not the case (see below).

Interpretation

The disturbed layering in unlithified sand adjacent to vertical chimneys is interpreted as the result of sand fluidization. Fluid injection in unlithified sands increases the pore fluid pressure which can lead to sand liquefaction and/or fluidization (liquidization; Maltman and Bolton 2003). Unlithified sand has no cohesion and is easily liquidized, whereas clay, even at very shallow burial, is more cohesive and is more prone to diapiric processes. Brecciation and updoming characteristic of fluid injection at greater depths do not occur in unlithified sands.

The extent of the disturbed sand was mapped on the basis of time slices at 20-ms intervals (the maximal extent of deformation in part of the study area is indicated in Fig. 10). The Late Tertiary sand deformation is outlined in yellow. It illustrates how the deformation spreads out from initially focused injection points. From this, the volume of disturbed sediment as a result of fluid injection was estimated to be about 6.7650 km³. This is equivalent to about 32% of the entire volume of the unconsolidated Tertiary section and indicates the large amounts of fluids that were injected in this area. Although sand fluidization is also possible by water injection from formation water due to a sudden rise in hydraulic head (Hurst et al. 2003; Draganits et al. 2003), the enormous size of the disturbed zone leads to the conclusion that additional fluid sources were required to fluidize this amount of sand (Hurst et al. 2003). Because of the close association with the upper part of the seismic chimneys, it is interpreted that hydrocarbon fluids and gases were injected laterally from the vertical chimney. Similar fluid intrusion patterns are obtained when vertical flow is simulated along a vertical conduit (e.g. a fault or a chimney) enclosed by shale, when the conduit crosses permeable aquifer units (Roberts et al. 1996; Lisk et al. 2000). The sand fluidization structures only occur within the unlithified sands and were not logged in the

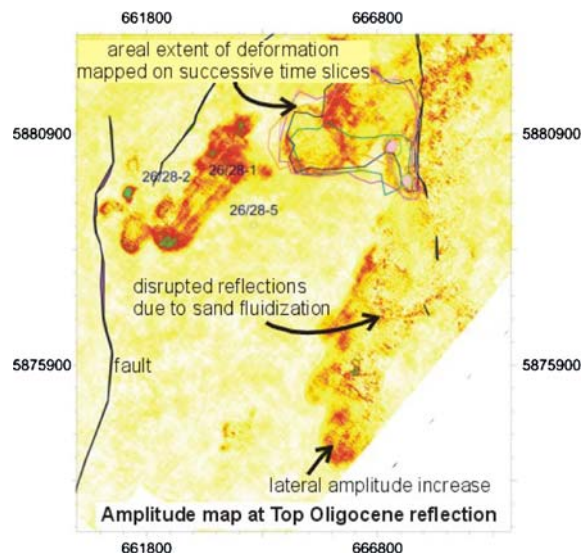


Fig. 9 Amplitude map of the Top Oligocene reflection showing sediment deformation related to fluid injection in unconsolidated sand

wells, therefore there are no lithological parameters (e.g. permeability of fluidized vs. undisturbed sands) available to estimate the amount of fluid that passed through (cf. Hurst et al. 2003).

The timing of vertical fluid injection is difficult to estimate from the seismic data alone. In theory, fluid injection could have occurred at any time since the Late Cretaceous, the onset of hydrocarbon generation in the Porcupine Basin. Seismic chimneys disrupt Eocene strata, caused fluidization in unconsolidated Tertiary sands and gave rise to pockmarks at the sea floor. The lower-most indication of sand fluidization is a V-shaped bright spot at 1 s TWT, about 450 m below the sea floor. From literature, it is known that sand fluidization occurs generally at depths shallower than 500 m, and usually deeper than 200 m. Hence, the fluidization structures are not older than Late Tertiary – Quaternary. If the lobe-shaped amplitude anomalies at the top Early Eocene and top Oligocene are extrusive sediment flows, it argues for repetitive fluid injection pulses initiated during or after the Early Eocene. The deformation in the unlithified sand layers would thus be multi-phased, with syn-depositional sediment extrusions and later post-depositional fluidization.

Sediment surface: dispersed pockmark distribution over localized vertical fluid migration pathways

High-resolution site survey data were available over the southern half of the study area (Fig. 1), where the Cretaceous sequence is very thick and only a few isolated chimneys occur. Surface and subsurface site survey data show numerous indications of fluid migration and gas accumulation in the shallow subsurface and of gas seepage at the sea floor (pockmarks):

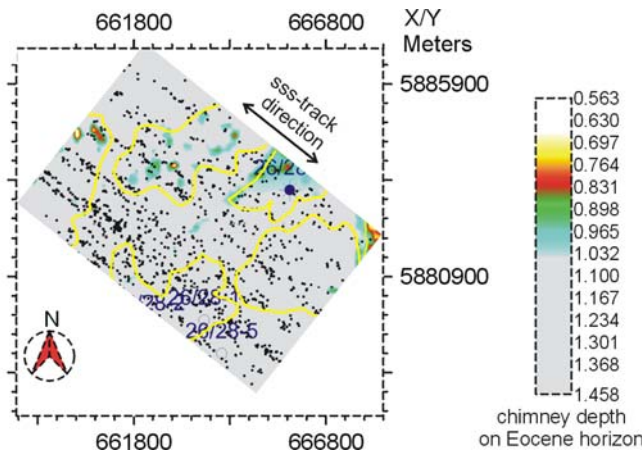


Fig. 10 Pockmark distribution (*black dots*) mapped from analog sidescan sonar profiles in the southern part of the study area superimposed on a location map of seismic chimneys in the same area. The *yellow lines* mark the maximal extent of sand deformation mapped from the 3D seismic data

- *Pockmarks*: About 1100 pockmarks were mapped from analogue field data (see also Games 2001). The pockmarks (Fig. 10) do not show any obvious alignments (apart from an alignment along the profile tracks related to data quality and incomplete coverage). They occur over the entire area with only a few clusters apparent. These clusters do not appear to be related to any detectable feature in the subsurface.
- *Interstitial gas*: Subbottom profiles show areas of acoustic blanking related to gas accumulation in the subsurface. These gas accumulations seem to occur mainly along ploughmarks and channels, probably related to coarser-grained sediment fill (see also Games 2001).
- *Columnar disturbances*: On subbottom profiles narrow vertical wipe-out areas occur abundantly throughout the study area. They are often interpreted as fluid escape features but do not seem to be associated with pockmarks at the surface.
- *Enhanced reflections*: High-resolution seismic profiles show areas with lateral enhanced reflections, also an indication of interstitial gas. These zones of enhanced reflections were also detected on the 3D seismic data.

Interpretation

The occurrence of pockmarks, acoustic blanking and columnar disturbances not appear to correlate with observed fluid migration pathways on the 3D seismic data. Figure 10 shows the pockmark distribution (with obvious alignment along the tracks) superimposed on a location map of the seismic chimneys. This area has only a few seismic chimneys, mainly located in the north-eastern of the site survey area. There appears to be no correlation between pockmark distribution and the

occurrence of chimneys or of the sand deformation areas. Figure 11 shows the pockmark distribution over a gradient map of the sea floor that highlights the occurrence of iceberg ploughmarks. Again, the extent of sand deformation is shown in yellow. In some places, pockmarks appear to line up or cluster at the edges of large ploughmarks. This suggests that ploughmark distribution asserts more control on the location of seabed seepage than the subsurface feeder systems.

The Plio-Pleistocene glaciomarine drift consists of a fine-grained deposit of glacio-marine clays with silty to sandy lenses and forms a seal over the permeable Tertiary sandstones. Detailed horizon picking from subbottom profiles and from the shallow part of the 3D seismic volume allowed us to distinguish four, possibly five, horizons with randomly-oriented iceberg ploughmarks. On subbottom profiles, blanking attributed to interstitial gas preferentially occurs in ploughmarks and buried channels (Fig. 12). Since no active faults go through the seabed, migration pathways are controlled by vertical and lateral permeability changes and lateral migration along coarser-grained ploughmarks and channels probably becomes more important. Since at least four stacked levels of randomly orientated ploughmarks occur, gas will be spread in all directions when migrating through this interval and a random pockmark distribution seems the logical outcome. Results from other recent studies concerning pockmark distribution at the Zaire fan (Gay et al. 2003) also indicated that pockmarks lined up along the flanks of a buried sandy channel along which fluids migrated laterally. Seafloor maps extracted from 3D seismic data in the Niger delta also show pockmark alignments along buried channels, but also along shallow faults (Haskell et al. 1999).

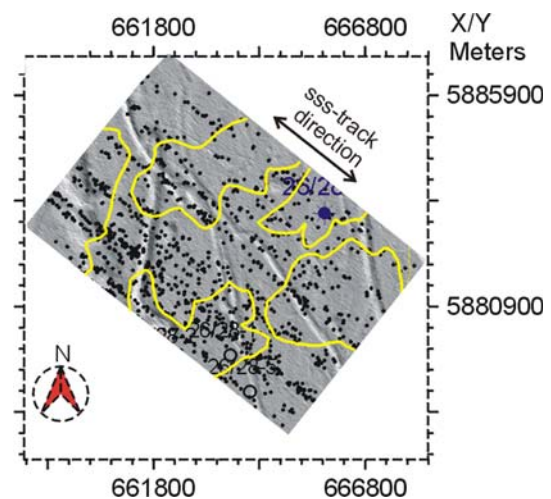


Fig. 11 Distribution of pockmarks (*black dots*) superimposed on the sea floor gradient map which highlights the presence of iceberg ploughmarks at the sea floor. The maximal extent of sand deformation is also indicated (*in yellow*)

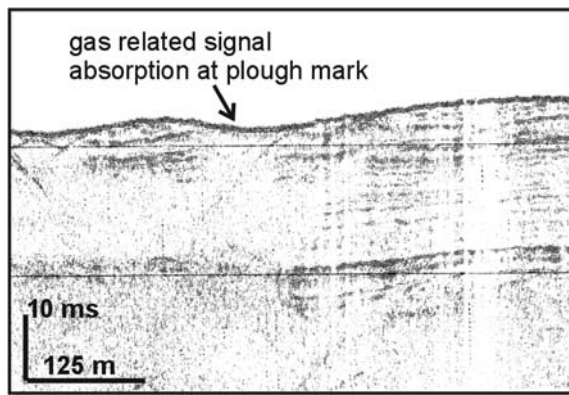


Fig. 12 Example of part of a 3.5 KHz subbottom profile through an iceberg ploughmark with blanking probably due to gas accumulation

Synthesis and conclusions

The data from the Connemara field area document fluid migration from the deep to the shallow subsurface and to the seafloor as follows:

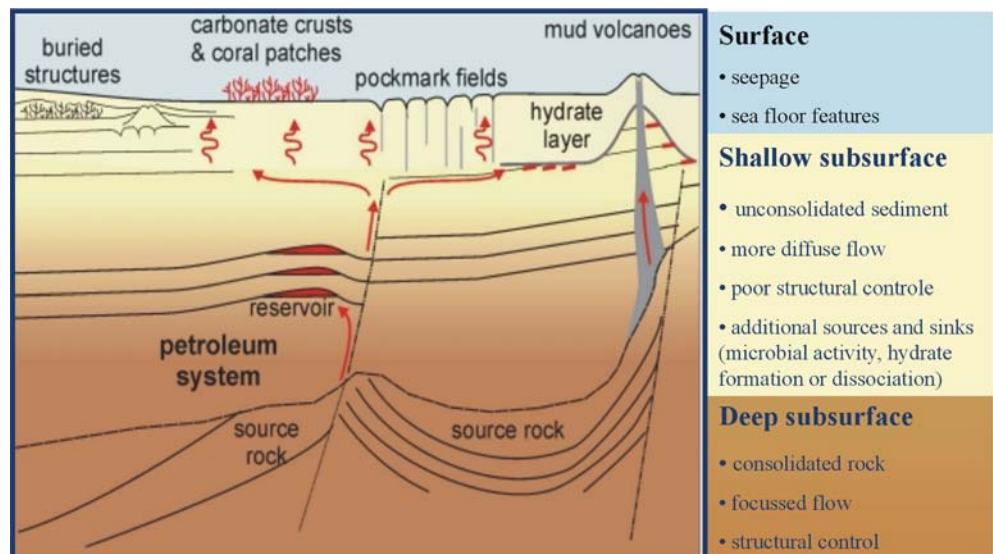
- Primary migration from the source in the central Porcupine basin to traps at the Jurassic/Cretaceous (J/C) unconformity in the Connemara field area.
- At traps where the J/C unconformity is overlain by a thick Cretaceous mud rock sequence tall isolated chimneys occur. These chimneys are interpreted to be formed by vertically propagating hydrofractures and are thought to be the main pathways for localized flow of hydrocarbons to shallow depths.
- At traps where the J/C unconformity is shallow and not overlain by thick mud rock sequences, many small vertical chimneys occur. In this case, since no effective seal is present, the fluid flow mechanism is probably not only overpressure-driven flow through hydrofractures but also buoyancy flow through permeable

rocks. Only at intermediate seals can hydrofractures occur.

- Lateral flow occurs at dipping sandstone levels (Early Eocene) and smaller chimneys root in this permeable layer.
- When the vertical chimneys reach unlithified sand layers, large-scale sand disturbances occur, probably by fluidization following lateral fluid injection from the vertical propagating chimneys.
- Intervening clay layers are compacted and form intermediate seals. Breaching of these seals triggers a new event of upward fluid flow and causes sediment injection into the overlying sands.
- About 70 m of glacio-marine drift seals off the unlithified Tertiary section. This seal was not breached by overpressured fluid and fluid migration probably occurred by diffuse flow through stacked sand-silt lenses in channels and iceberg ploughmarks.
- At the seafloor, pockmark distribution is largely independent from the location of chimneys and sand deformation in the subsurface. This indicates a transition from focused to diffuse fluid flow at the base of the Plio-Pleistocene glaciomarine drift.

The Connemara field area study shows how focused vertical fluid flow in the subsurface may lead to almost randomly distributed gas seeps at the sea floor. It also demonstrates the importance of the shallow subsurface for source to seafloor fluid migration (Fig. 13): whereas fluid migration in the deep subsurface is mostly focused along well established, mainly structurally controlled pathways, migration in the unconsolidated shallow subsurface seems to be more diffuse, controlled by lateral variations in sediment properties and hydraulic pressure. Furthermore, fluid migration is difficult to detect. Episodes of fluid expulsion in the past may perhaps only be detected by buried sea floor structures related to this event, for example, mud volcanoes, pockmarks and carbonate structures.

Fig. 13 Concluding overview sketch of source-to-seafloor fluid migration characteristics. Fluid flow in the deep subsurface occurs along faults, dipping beds and injection features and is thus mainly structurally controlled. In the unconsolidated shallow subsurface, fluid flow may be more diffuse and controlled by sedimentary and hydraulic parameters. Sea floor seepage is marked by sea floor structures. Past events of fluid expulsion can only be detected by buried seep-related structures on seismic data



Acknowledgements The data for this study were provided by Statoil Ireland Ltd. and by the Petroleum Affairs Division (PAD,DCMNR) in Dublin, Ireland. Part of the mapping and interpretation was carried out by students as part of their research project at Ghent University. PVR is a research fellow of the Foundation of Scientific Research—Flanders. Peter Croker and Roar Heggland reviewed this paper and suggested lot of corrections to the original manuscript.

Appendix 1: Petrophysics, seismic horizons, lithology, and stratigraphy for well 26/28-1

Mean	GR_f	RHOB_f	DT_f	NPHI_f	logILD_f	ILD_f	Sample #	end cell	10946
Class 1	55.33	2.48	74.11	13.99	1.08	12.156	502	nbr class	8
Class 2	86.35	2.51	86.74	27.44	0.57	3.712	2175		
Class 3	36.64	2.12	117.29	34.05	-0.08	0.838	1274		
Class 4	79.87	2.29	114.69	35.51	0.34	2.164	2009		
Class 5	71.77	2.31	101.66	35.02	0.42	2.621	2013		
Class 6	106.41	2.44	78.07	29.32	0.79	6.168	881		
Class 7	103.52	2.60	71.73	18.73	1.00	10.115	1394		
Class 8	48.53	2.40	81.93	18.73	0.36	2.299	697		
Class-9									
Class-10									
Class-11									
Total nbr of samples							10945		
Std dev	GR_f	RHOB_f	DT_f	NPHI_f	logILD_f			Vp_f	
Class 1	14.06	0.12	9.07	7.36	0.06			4112.59	reservoir SST
Class 2	13.41	0.08	9.24	5.24	-0.16			3513.82	alternance SST / MDT
Class 3	9.43	0.06	9.17	2.50	-0.01			2598.61	Albian massive SST
Class 4	14.38	0.07	9.59	2.87	-0.11			2657.56	MST (L. Apt., L. Kimm)
Class 5	12.12	0.08	9.43	4.27	-0.14			2998.25	LST / dolomitic MST
Class 6	16.75	0.12	8.90	4.79	0.12			3904.40	Carb. MST / SLTST
Class 7	12.38	0.05	3.09	4.43	-0.03			4249.52	Carb. MST / SLTST
Class 8	14.80	0.09	8.13	5.16	-0.06			3720.35	LST layers
Class-9									
Class-10									
Class-11									

	Depth [mbss]	Aver. DT [us/ft]	Aver. Vplog [m/s]	VSP Vp [m/s]	Base depth [sec TWT]	Aver. RHOB [g/cc]	Aver. DPHI [g/cc]	Aver. NPHI [%]	Aver. GR [gAPI]	Aver. ILD [ohm.m]	Thickness [m]
Seafloor	374.00		1500.00		0.499						
Brown											
Dark-red											
Red	1073.20	148.59	2051.23		1.180	1.96	41.75	44.08	74.07	0.74	699.20
Str-Hz 1	1078.50	93.44	3261.92		1.184	2.25	24.27	31.96	18.22	2.13	5.30
Orange	1284.10	120.90	2521.18		1.347	2.11	33.01	34.26	32.16	0.79	205.60
Str-Hz 2	1389.10	109.51	2783.24		1.422	2.20	27.13	33.50	50.74	1.37	105.00
Purple	1929.40	107.02	2848.13		1.802	2.29	21.79	34.80	71.11	2.31	540.30
Violet											
Str-Hz-3											
Light-blue											
Apple-green											
Str-Hz 4	1949.10	90.79	3357.30		1.813	2.36	17.53	25.80	69.08	5.04	19.70
Light green	2141.50	108.22	2816.60		1.950	2.33	19.12	36.31	89.31	2.51	192.40
Str-Hz 5	2219.50	92.63	3290.68		1.997	2.43	13.54	30.28	82.88	3.35	78.00
Str-Hz 6	2246.30	86.80	3511.56		2.013	2.37	16.91	23.46	68.47	6.73	26.80
Yellow	2709.10	86.38	3528.77		2.275	2.47	10.68	25.40	77.41	3.26	462.80
Str-Hz 7	3196.10	72.64	4196.12		2.507	2.56	5.15	22.58	103.80	9.28	487.00
Dark green	3224.10	70.61	4316.97		2.520	2.56	5.50	13.20	92.05	8.03	28.00

Depth (mbrf)	BasinLab section stratas
Sea surface	25.90
Seafloor	399.90
Brown	A1
Dark-red	A2
Red	A3
Str-Hz 1	A4
Orange	A5
Str-Hz 2	A6
Purple	A7
Violet	A8
Str-Hz-3	A9
Light-blue	A10
Apple-green	A11
Str-Hz 4	A12
Light green	A13
Str-Hz 5	A14
Str-Hz 6	A15
Yellow	A16
Str-Hz 7	A17
Dark green	A18
	A19

Appendix 2: Petrophysics, seismic horizons, lithology, and stratigraphy for well 26/28-5

Mean	GR_f	RHOB_f	DT_f	NPHI_f	logILD_f	ILD_f	Sample #	end cell	11269
Class 1	22.05		141.43		0.02	1.037	1685	nbr class	8
Class 2	82.87		79.02		0.71	5.138	541		
Class 3	82.99		101.18		0.45	2.837	3008		
Class 4	109.14		98.03		0.39	2.481	2498		
Class 5	33.81		155.63		0.03	1.076	1210		
Class 6	84.61		85.22		0.16	1.445	320		
Class 7	28.86		114.16		-0.08	0.839	1108		
Class 8	34.30		104.76		0.23	1.713	898		
Class-9									
Class-10									
Class-11									
Total nbr of samples							11268		
Std dev	GR_f	RHOB_f	DT_f	NPHI_f	logILD_f				
Class 1	9.29		6.87		0.00			Vp_f	
Class 2	21.22		7.69		-0.01			Class 1	2155.09 lithified marl/sand/silt
Class 3	16.30		11.00		-0.20		26/28-05	Class 2	3857.44 calc. MST/interbedded DOL
Class 4	9.89		9.20		-0.16		3 variables	Class 3	3012.40 MST
Class 5	9.30		7.27		0.00			Class 4	3109.19 MST+/-DOL / SST
Class 6	11.49		5.51		-0.03			Class 5	1958.53 sublithified SST/marl
Class 7	10.73		9.34		-0.01			Class 6	3576.72 reservoir SST
Class 8	17.25		14.82		-0.05			Class 7	2670.05 Albian massive SST
Class-9								Class 8	2909.58 LST / LST-rich layers
Class-10									
Class-11									

	Depth	Aver. DT	Aver. Vp _{log}	VSP Vp	Base depth	Aver. RHOB	Aver. DPHI	Aver. NPHI	Aver. GR	Aver. ILD	Thickness
	[mbs]	[us/ft]	[m/s]	[m/s]	[sec TWT]	[g/cc]	[g/cc]	[%]	[gAPI]	[ohm.m]	[m]
Seafloor	376.00		1500.00		0.501						
Brown	705.00	154.35	1974.68	2013.00	0.835				34.38	1.05	329.00
Dark red	997.40	141.52	2153.81	2013.00	1.106				20.61	1.07	292.40
Red	1141.00	125.32	2432.12	2013.00	1.224				33.40	1.38	143.60
Str-Hz 1	1151.00	94.48	3226.20		1.230				15.85	2.23	10.00
Orange	1356.00	113.22	2692.00	2622.00	1.383				25.29	0.92	205.00
Str-Hz 2	1469.00	104.06	2929.06		1.460				43.14	1.36	113.00
Purple	1849.00	109.58	2781.44	2731.00	1.733				70.94	2.34	380.00
Violet	1910.00	98.76	3086.41	2976.00	1.773				86.63	2.75	61.00
Str-Hz 3	1965.00	97.87	3114.47		1.808				91.51	3.05	55.00
Light blue	2005.00	100.22	3041.24	3065.00	1.834				99.22	3.17	40.00
Apple green	2187.00	99.46	3064.57	3072.00	1.953				106.08	2.78	182.00
Str-Hz 4	2275.00	85.65	3558.78		2.002				88.89	1.66	88.00
Light green	2638.00	91.51	3330.72	3071.00	2.220				106.75	2.98	363.00
Str-Hz 5	2738.00	80.63	3780.05		2.273				105.20	4.26	100.00
Str-Hz 6	2743.80	78.37	3889.32		2.276				67.00	2.10	5.80
Yellow											
Str-Hz-7											
Dark-green											

Depth (mbrf)	Base depth (from VSPs)	BasinLab section stratas
Sea surface	25.00	
Seafloor	401.00	0.50
Brown	730.00 Base Eocene-Recent sublithic SST	0.83
Dark red	1022.40 Base Eocene quartzose SST	1.12
Red	1166.00 Base Tertiary	1.26
Str-Hz 1	1176.00 Base Chalk fm	
Orange	1381.00 Base Albian massive SST	1.43
Str-Hz 2	1494.00 Base Albian SST (coarsening-upward cycles)	
Purple	1874.00 Base Albian / Aptian MST	1.79
Violet	1935.00 intra Neocomian marker	1.83
Str-Hz 3	1990.00 Base Neocomian	
Light blue	2030.00 intra Portlandian marker	1.89
Apple green	2212.00 Base E. Portlandian to Kimmeridgian MST	2.01
Str-Hz 4	2300.00 Base reservoir SST	
Light green	2663.00 intra E. Portlandian - Kimmeridgian DOL marker	2.30
Str-Hz 5	2763.00 Base E. Kimmeridgian - Bajocian MST	
Str-Hz 6	2768.80 Base E. Kimmeridgian - Bajocian SST (reservoir)	
Yellow		
Str-Hz-7		
Dark-green		

References

- Boehm A, Moore JC (2002) Fluidized sandstone intrusions as an indicator of paleostress orientation, Santa Cruz, California. *Geofluids* 2:147–161
- Croker PF, Shannon PM (1987) The evolution and hydrocarbon prospectivity of the Porcupine Basin, offshore Ireland. In: Brooks J, Glennie K (eds) *Petroleum Geology of North West Europe*. Graham and Trotman, London, pp 633–642
- Draganits E, Grasemann B, Schmid HP (2003) Fluidization pipes and spring pits in a Gondwanan barrier-island environment: Groundwater phenomenon, palaeo-seismicity or a combination of both? In: Van Rensbergen P, Hillis RR, Maltman AJ, Morley CK (eds) *Subsurface sediment mobilisation* vol 216. Geological Society of London Special Publications, pp 109–121
- Engelder T, Leftwich JT Jr (1997) A pore-pressure limit in overpressured South Texas oil and gas fields. In: Surdam RC (ed) *Seals, traps, and the petroleum system: AAPG Memoir*, vol 67, pp 255–267
- Games KP (2001) Evidence of shallow gas above the Connemara oil accumulation, Block 26/28, Porcupine Basin. In: Shannon PM, Haughton PDW, Corcoran DV (eds) *The Petroleum Exploration of Ireland's offshore basins*. Geological Society, London, Special Publications, vol 188, pp 361–373
- Gay A, Lopez M, Cochonat P, Sultan N, Cauquil E, Brigaud F (2003) Sinuous pockmark belt as indicator of a shallow buried turbiditic channel on the lower slope of the Congo basin, West African margin. In: Van Rensbergen P, Hillis RR, Maltman AJ, Morley CK (eds) *Subsurface sediment mobilisation*. Geological Society of London Special Publications, vol 216, pp 173–189
- Haskell N, Nissen S, Hughes M, Grindhaug J, Dhanani S, Heath R, Kantotowicz J, Antrim L, Cubanski M, Nataraj R, Schilly M, Wigger S (1999) Delineation of geologic drilling hazards using 3-D seismic attributes. *Lead Edge* 18(3):373–382
- Heggland R (1997) Detection of gas migration from a deep source by the use of exploration 3D seismic data. *Mar Geol* 137:41–47
- Hurst A, Cartwright J, Duranti D (2003) Fluidization structures produced by upward injection of sand through a sealing lithology. In: Van Rensbergen P, Hillis RR, Maltman AJ, Morley CK (eds) *Subsurface sediment mobilisation*. Geological Society of London Special Publications, vol 216, pp 123–138
- Lewis JC, Byrne T (1996) Deformation and diagenesis in an ancient mud diapir, southwest Japan. *Geology* 24:303–306
- Lisk M, Faiz MM, Bekele EB, Ruble TE (2000) Transient fluid flow in the Timor Sea, Australia: implications for prediction of fault seal integrity. *J Geochem Explor* 69–70:607–613
- MacDonald H, Allen PM, Lovell JPB (1987) Geology of oil accumulation in Block 26/28, Porcupine Basin, offshore Ireland. In: Brooks J, Glennie K (eds) *Petroleum Geology of North West Europe*. Graham and Trotman, London, pp 643–651
- MacLeod MK, Hanson RA, Bell CR, McHugo S (1999) The Alba Field ocean bottom cable seismic survey: Impact on development. *Lead Edge* 18(11):1306–1312
- Maltman AJ, Bolton (2003) How sediments become mobilized. In: Van Rensbergen P, Hillis RR, Maltman AJ, Morley CK (eds) *Subsurface sediment mobilisation*. Geological Society of London Special Publications, vol 216, pp 9–20
- Moore JG, Shannon PM (1995) The Cretaceous succession in the Porcupine Basin, offshore Ireland: facies distribution and hydrocarbon potential. In: Croker PF, Shannon PM (eds) *The Petroleum Geology of Ireland's Offshore Basins*. Geological Society of London Special Publications, vol 93, pp 345–370
- Revil A (2002) Genesis of mud volcanoes in sedimentary basins: a solitary wave-based mechanism. *Geophys Res Lett* 29(12):81–84
- Roberts SJ, Nunn JA, Cathles L, Cipriani FD (1996) Expulsion of abnormally pressured fluids along faults. *J Geophys Res* 101:28231–28252
- Shannon PM (1991) The development of Irish offshore sedimentary basins. *J Geol Soc Lond* 148:181–189
- Stump BB, Flemings PB (2000) Overpressure and fluid flow in dipping structures of the offshore Gulf of Mexico (E.I. 330 Field). *J Geochem Explor* 69–70:23–28
- Van Rensbergen P, Morley CK, Ang DW, Hoan TQ, Lam NT (1999) Structural evolution of shale diapirs from reactive rise to mud volcanoes at the Baram Delta (offshore Brunei Darussalam). *J Geol Soc Lond* 156:633–650
- Ziegler PA (1982) *Geological atlas of Western and Central Europe*. Shell Internationale Petroleum maatschappij BV