

# Pressure cells and pressure seals in the UK Central Graben

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Received 16 January 1996; accepted 24 February 1996

The Central Graben of the North Sea is characterised by high levels of overpressure (up to 40 MPa overpressure at 4500 m depth). We present pressure data for Cenozoic and Mesozoic reservoirs. Palaeocene sandstones control pressures in Tertiary mudstones and Cretaceous Chalk by acting as a regional 'drain'. We divide the Jurassic into 18 pressure cells. The rift structure of the Graben controls the magnitude of pressure in each cell. Lateral hydraulic communication exists over 10 km distance between deeply-buried terraces (>5000 m depth) and shallow structural highs (<4500 m depth). Lateral communication increases pressure in the structurally-elevated sandstones to the minimum stress. This dynamic process produces zones of vertical fluid flow on the Forties–Montrose High, termed Leak Points. Vertical flow at Leak Points produces a 20 MWm<sup>-2</sup> heat flow anomaly and controls hydrocarbon retention. Leak Points are water-wet, while deep terraces in hydraulic communication with Leak Points are condensate-bearing. The Kimmeridge Clay Fm. forms the pressure seal in deep terraces. Copyright © 1996 Elsevier Science Ltd

**Keywords:** overpressure; pressure seals; North Sea

## Introduction

Abnormal fluid pressure is commonly encountered in deep (>3 km) hydrocarbon reservoirs. Overpressure influences many fluid-related aspects of geology, including diagenesis and reservoir quality (e.g. Burley, 1993), hydrocarbon generation (Price and Wenger, 1992) and hydrocarbon migration (England *et al.*, 1987). Overpressure also forms a hazard for drilling wells, and so directly impacts the safety and economics of hydrocarbon exploration. An increased understanding of the distribution, origins and effects of overpressure will advance prospect evaluation in overpressured basins.

The occurrence of overpressures in many sedimentary basins world-wide is noted by Bradley (1975), who proposes that low-permeability barriers, termed pressure seals, restrict fluid flow in deep basins. Powley (1990) and Hunt (1990) propose the paradigm of the pressure cell (or pressure compartment). A pressure cell is a body of rock containing overpressured fluids that are internally in free hydraulic communication. Pressure gradients within cells are parallel to the hydrostatic pressure gradient. Free fluid flow between pressure cells is restricted by low-permeability barriers termed pressure seals. Common pressure–depth gradients in wells define pressure cells; plots of pressure against depth form the principal tool in pressure analysis. Changes in the pore pressure gradient define pressure seals, forming the 'transition zones' of

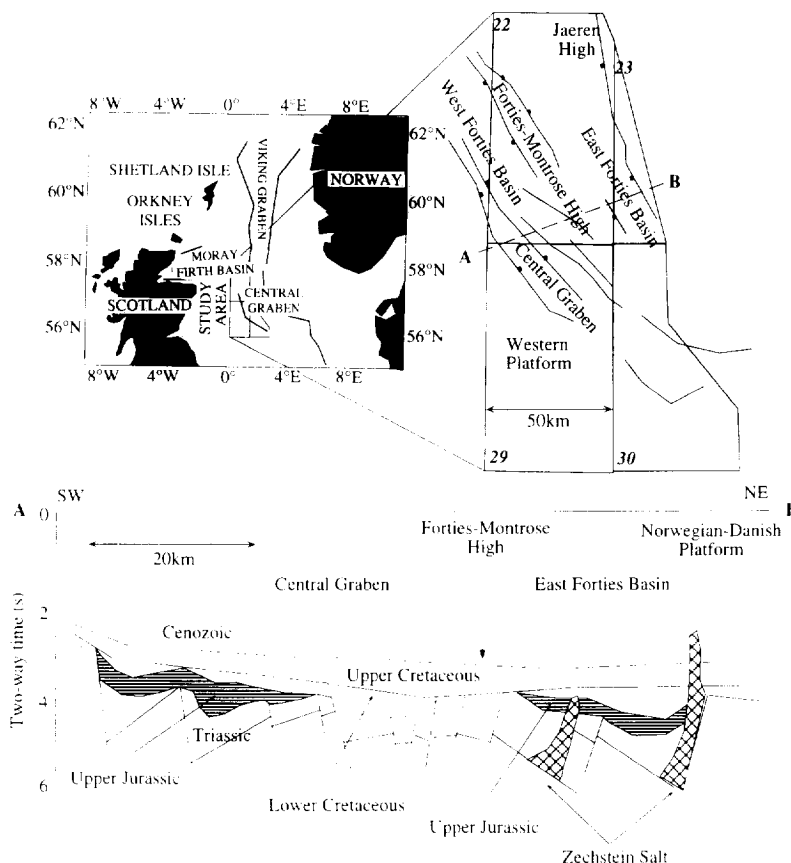
drilling terminology. Recent work has attempted to decipher the geological characteristics and the mechanisms of formation of pressure seals (e.g. Tiggert and Al-Shaieb, 1990; Weedman *et al.*, 1992; Whelan *et al.*, 1994). Overpressured basins may be viewed as 'static' systems, where fluid flow is prevented by impermeable, diagenetically-cemented seals (e.g. Hunt, 1990). Bredehoeft *et al.* (1994) and Neuzil (1995) present a contrasting 'dynamic' paradigm of overpressured basins, where fluid flow is restricted—but not totally prevented—by low-permeability rocks.

In this paper we investigate the hydrogeology of the highly overpressured Central Graben of the North Sea. We present pressure data from a range of stratigraphic intervals. The pressure distribution in example wells is used to illustrate the variation of overpressure with depth and stratigraphy. We delineate pressure cells and pressure seals across the Graben. This dataset allows new insight into the distribution of overpressure in the region. We interpret the pressure distribution as signifying fluid flow in a dynamic, hydraulically-continuous system. We discuss the implications of this model of overpressure for hydrocarbon entrapment in the Central North Sea.

## The Central North Sea

The Central North Sea is the southernmost arm of the North Sea rift. The syn-rift Jurassic structure of the Central Graben is complex, with a series of NE-dipping tilted fault blocks, bounded by NW–SE oriented faults (Roberts *et al.*, 1990). A simplified map and section of the Central Graben (Figure 1) show an eastern and a western graben, separated by the axial Forties–Montrose High.

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**Figure 1** Location and schematic structure of the Central Graben of the North Sea (after Roberts *et al.*, 1990)

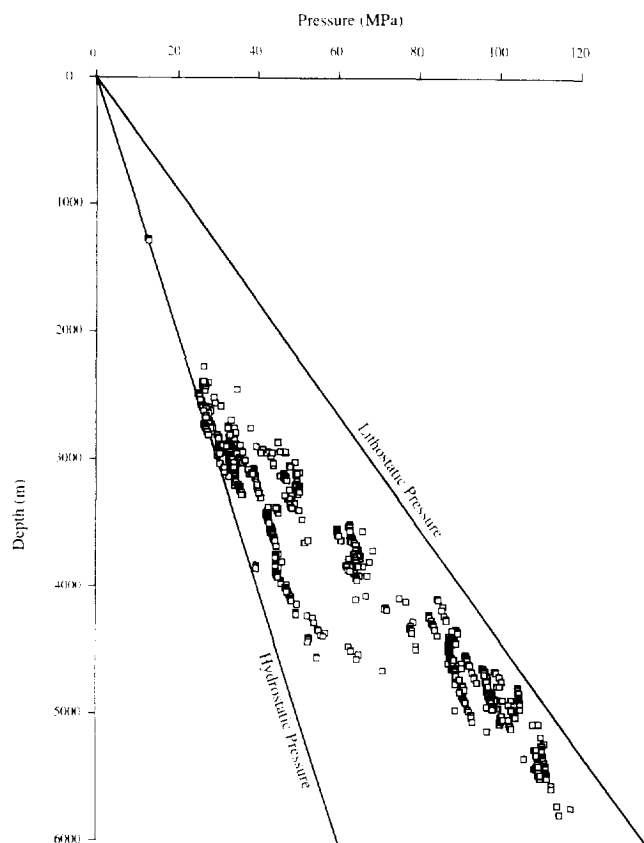
Jurassic structure strongly influences the distribution of the syn-rift Jurassic sediments (Rathey and Hayward, 1993). Upper Jurassic sediments of the Central Graben are termed the Humber Group (Price *et al.*, 1993). This group contains sandstones of the Fulmar Formation. This formation is the principal reservoir sandstone in the Mesozoic of the Graben. The Humber Gp also contains mudstones of the Kimmeridge Clay Formation (KCF), the source rock for most of the North Sea's hydrocarbons (Cayley, 1987). The KCF is mature for gas generation over much of the Central Graben (Cornford, 1994). Post-rift sediments form a thick blanket over the Central Graben. Lower Cretaceous mudstones of the Cromer Knoll Group (CKG) pass into the Upper Cretaceous Chalk Group. Thick, permeable Palaeocene sandstones overly the Chalk Gp over the axial parts of the Graben, forming major hydrocarbon reservoirs. The Palaeocene sandstones become thinner and discontinuous in the south of the Central Graben (Reynolds, 1994). Accelerating subsidence rates in the Cenozoic led to the deposition of up to 3 km of mudstones, of which 1 km has been deposited in the Quaternary (Thorne and Watts, 1989).

The Fulmar Fm. in the Central Graben is deeply buried (3–5 km and up to 200 °C) and highly overpressured (up to 40 MPa above hydrostatic pressure). The deep Fulmar Fm. is termed the high-pressure/high-temperature (HPHT) play. The overpressures in the Central Graben have attracted considerable interest due to the difficulties of drilling HPHT hydrocarbon targets, and several studies of the overpressure distribution have been published. Cayley (1987) presents a detailed analysis of the distribution of overpressure in the Jurassic sandstones. Hunt

(1990) identifies an upper and lower pressure cell, extending across the Central Graben and separated by diagenetically-cemented seals. Mudford *et al.* (1991) present a simulation of overpressure in the southern Central Graben, and propose that overpressure in the Jurassic sandstones was caused by rapid basin subsidence and the restriction of vertical flow by the low-permeability aquitard formed by the Chalk and Cromer Knoll Groups. Gaarenstroom *et al.* (1993) present maps and pressure-depth plots of pressures in Jurassic sandstones; pressure cells on the western margin of the Graben were delineated, and the possible origins of overpressure in the region were discussed. They propose a generalised model of the control of overpressure by hydraulic fracturing of the top seal in pressure cells.

### Sources of pressure data

All data presented in this paper were derived from 70 released wells. These data were extracted from a larger database of 280 confidential wells provided by Elf Enterprise Caledonia. We used Repeat Formation Tests (RFTs) and mudweight to study the pressure distribution in the Graben. RFTs measure the formation pressure at a specific depth in a permeable formation. A series of RFT measurements run over 100–500 m depth allowed the construction of a pressure–depth gradient, from which pressure cells were identified. Comparison of pressure depth gradients between wells with varying fluid types requires data correction (Buhrig, 1989); here we refer solely to pressures in water. In low-permeability formations, RFTs are rarely run and may be inaccurate.



**Figure 2** Regional RFT pressure–depth plot. Overpressure is indicated from 2500 m to a maximum drilled depth of 6000 m. There is no simple relationship between magnitude of overpressure and depth: at 4500 m depth, formation pressure may be close to hydrostatic pressure or close to lithostatic pressure. Numerous pressure gradients parallel to the hydrostatic pressure gradient can be defined, suggesting the presence of multiple pressure cells and the compartmentalisation of the basin fluids

However, indirect measurements of pressure can be used in low-permeability rocks. Drilling mud is used to counterbalance the pressure of the formation fluid. Mud density provides a continuous record of pressure throughout the well, giving a maximum limit to the formation pressure. An increase in mud weight may imply an increase in formation pressure, but increases in mud weight may be implemented by the drillers if high formation pressures are expected to be encountered, to allow an increase in the safety margin. Quality-control of the relationship of mud weight to formation pressure was achieved by monitoring mud gas (Mouchet and Mitchell, 1989). Gas influx into the borehole is controlled by the differential pressure between hole and formation. Rising gas levels suggest reduced differential pressure and thus suggest rising formation pressure. Leak-off Tests (LOTs) are used to determine the maximum safe mud weight that can be sustained by the formation without fracturing. It can thus be used as an approximation to the magnitude of the minimum stress in the well (Engelder and Fischer, 1994; Yassir and Bell, 1994).

### Pressure distribution in the Central North Sea

#### *Basin-scale pressure distribution*

On this largest scale of observation, the Central Graben is divided into an upper, hydropressed regime, generally occurring above 3000 m, and a lower, overpressured regime (Figure 2). Similar distributions are common in

sedimentary basins (Hunt, 1990). The boundary between normal pressures and overpressures is diffuse, occurring between 2500 m and 4000 m in individual wells.

#### *Cenozoic mudstones*

Quantitative pressure data is entirely absent from the thick Quaternary and Tertiary mudstone units of the basin. Additionally, mud weight is typically far in excess of formation pressure, and so is not indicative of pressure. Sonic logs and 'd'-exponent pressure evaluation (Darby, 1995) suggest that overpressure in the Cenozoic mudstones occurs from approximately 1000 m depth, and pressures decline to lower values above the Palaeocene sandstones. Although the magnitude of overpressure developed in the Cenozoic mudstones is not high compared to that of pre-Cretaceous strata, it may cause drilling problems.

#### *Palaeocene sandstones*

The Palaeocene sandstones are normally-pressured in the north of the study area (e.g. well 22/21-4) and are overpressured towards the south of the region (Figure 3). We found no relationship between Palaeocene sandstone overpressure and depth (Figure 3): pressures at 2800 m depth may be hydrostatic or 15 MPa in excess of hydrostatic pressure. Wells 29/4a-1a and 29/4a-2 demonstrate the presence of an upper, hydropressed interval overlying a lower, overpressured interval within the Palaeocene sandstones of these wells. RFTs in the northern Palaeocene sandstones define a fresh-water pressure gradient.

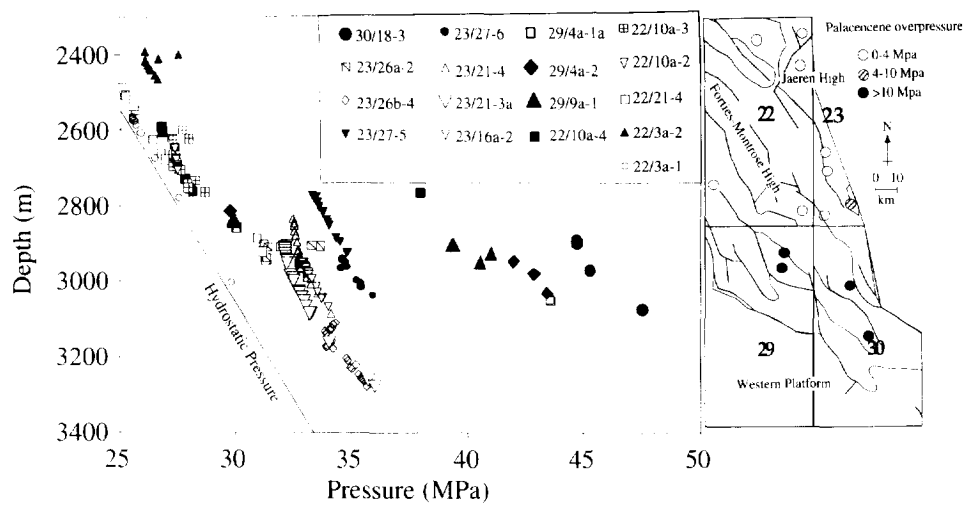
#### *Cretaceous Chalk*

Description of the pressure distribution within the Cretaceous Chalk was hampered by the paucity of quantitative data. Economic hydrocarbons have not been found in the Chalk in Quadrant 22 and so RFTs were seldom run. However, the upper formations of the Chalk in Quadrant 22 were found to be normally pressured (Figure 4). In Quadrants 23, 29 and 30, oil has been discovered in the Ekofisk and Tor formations, and so RFTs were recorded for permeable zones. These tests indicated that the Upper Chalk is overpressured in the south of the study area (Figure 4).

#### *Lower Cretaceous–Triassic*

RFT measurements within Central Graben pre-Cretaceous sandstones revealed a concentric pattern of abnormal pressure in the study area (Figure 5). Jurassic sandstones on the Western Platform are hydropressed. Overpressure increases towards the centre of the Graben from moderately overpressured marginal fault terraces (such as block 22/5b) towards central, highly overpressured fault blocks (such as block 29/5). The distribution of overpressure is complex in detail in the East Forties Basin and the central core of the Central Graben; the concentric distribution of overpressure is complicated by the presence of the axial Forties–Montrose High and satellite fault terraces, where relatively shallow wells (e.g. 22/30a-1, 30/1c-2) encountered high levels of overpressure.

In Jurassic reservoirs, pressure generally increases with increasing depth in the Graben (Figure 6). However, when



**Figure 3** Overpressure in Palaeocene sandstones. Pressures in Palaeocene sandstones are close to hydrostatic in the north of the study area (wells from Quadrant 22), but become increasingly overpressured towards the south and east of the study area (Quads 23, 29 and 30). This trend relates to the sedimentology of the submarine fans, which become thinner and discontinuous in the south of the Central Graben and towards the margins of the basin (Reynolds, 1994)

examined in detail it was evident that overpressure at any one depth may vary considerably. For example, the Fulmar sandstones of well 29/9c-4 and well 22/30a-1 occur at a similar depth of 4500 m, but have 15 MPa difference in observed pressures. The magnitude of overpressure developed within pre-Cretaceous sandstones correlates to both depth and geographical position in the Graben. The presence of distinct RFT pressure-depth gradients in the pre-Cretaceous sandstones suggested compartmentalisation and hydraulic separation of the sandstones into pressure cells.

RFTs provided an adequate description of pressure in the pre-Cretaceous aquifers of the Graben. However, a description of the pressure distribution in the Cretaceous Jurassic shale aquitards required a more complete examination. Figures 7-9 present detailed pressure data for wells penetrating deeply-buried Jurassic and Triassic fault blocks in the Central Graben, Forties-Montrose High and East Forties Basin. These plots allowed insight into the pressure seals in the region.

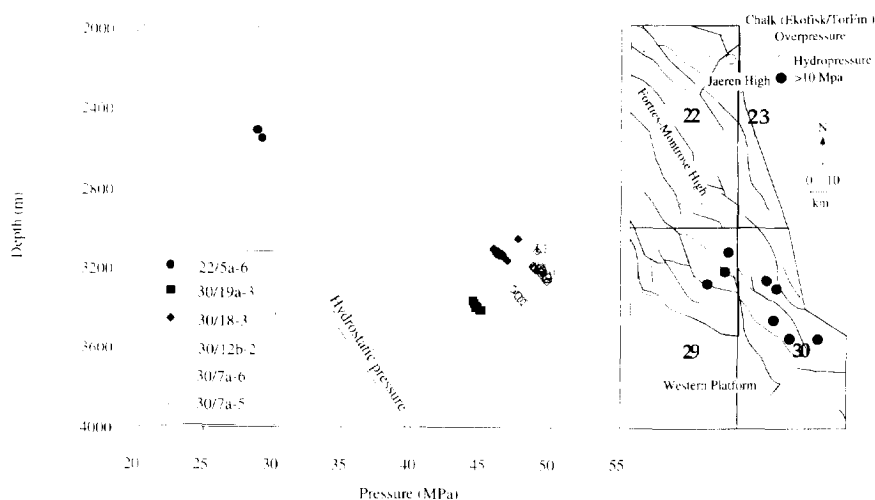
A degree of complexity was revealed by the plots, with

wells demonstrating several increases in pressure. A gradual increase in pressure was noted throughout the Lower Cretaceous mudstones in all wells. A further, much larger increase in pressure to the highest pressures recorded in the well occurred either within the Kimmeridge Clay Formation (wells 29/5b-4, 23/26a-7, and 29/5a-3) or at the top of the permeable pre-Cretaceous sandstone (wells 22/30a-1, 29/10-2 and 30/1C-2). Good quality-control of mud weight was available due to background and connection gases (up to 75% in some wells) suggesting balance between mud weight and formation pressure. Additional increases in pressure within the pre-Cretaceous sandstones were suggested by kicks in the gas condensate reservoirs of well 29/5a-3. A strong degree of reservoir compartmentalisation is implied.

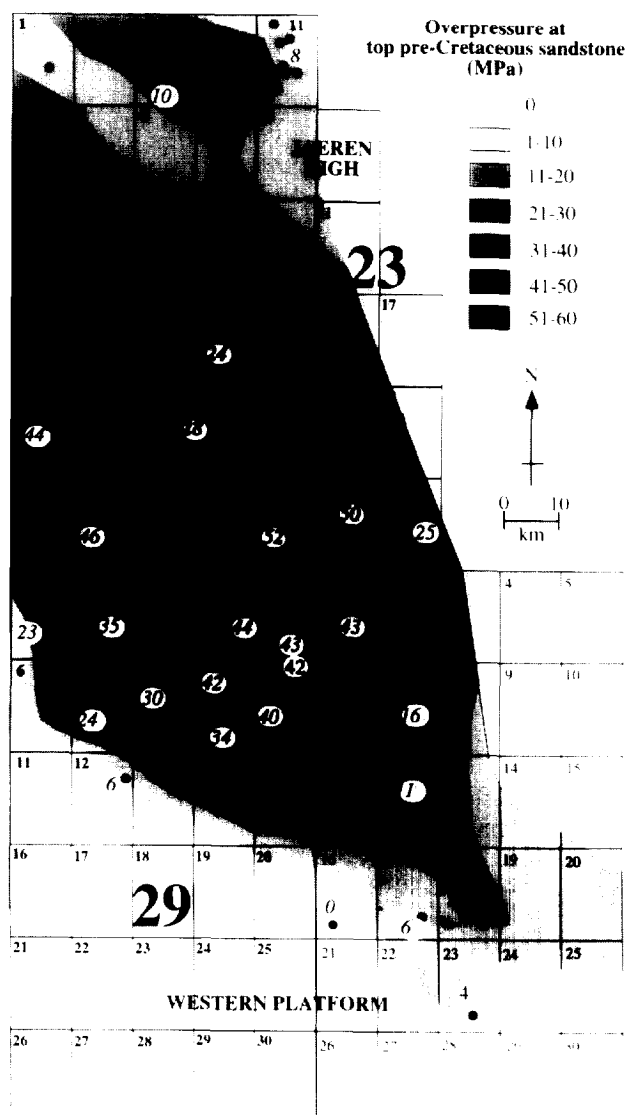
### Controls on the pressure distribution

#### Cenozoic

The distribution of overpressure in the Cenozoic mudstones is controlled by the low vertical permeability of



**Figure 4** Overpressure in Cretaceous Chalk. Pressures vary from close to hydropressure in the north of the Graben, to 15 MPa overpressure in the south. Although data is scarce, a trend of increasing overpressure towards the south of the study area may be noted. This relates to the distribution of the overlying Palaeocene sandstones, which drain the upper Chalk Group. Where the sandstones are thin, discontinuous and overpressured, fluid flow is restricted in the upper Chalk, which becomes overpressured



**Figure 5** Map of the areal distribution of overpressure in Jurassic sandstones of the Central Graben. Italic figures denote magnitude of overpressure; solid circles denote well position from which overpressure has been measured. A concentric pattern is evident. Jurassic sandstones are hydro pressured on the shallow Western Platform. Overpressure increases into the centre of the Graben, with extreme overpressure encountered in wells on the central section of the axial Forties–Montrose High and the adjacent fault terraces

these thick formations, which will inhibit vertical escape of fluids as the shales undergo compaction. Drainage of the shales downwards into the Palaeocene sandstones accounts for the reduction in pressure in the deepest shales.

The distribution of overpressure in the Palaeocene sandstones is a function of sandbody connectivity. The Palaeocene submarine fans are thickest in the north of Quadrant 22 (Reynolds, 1994). This thick, permeable, basin-wide sandsheet allows rapid fluid drainage towards the basin margins and consequently the unit remains hydro pressured. The fans decrease in thickness and lateral extent southwards. Sandbody distribution is also a function of depth, with the lowermost Andrew Formation thin and discontinuous in northern Quadrants 29 and 30 (Reynolds, 1994). Fluid flow in the Palaeocene is thus more restricted in the south of the Central Graben, and particularly in the lower sandstone formations,

accounting for the southward increase in overpressure and the two-cell profile in well 29/4a-1.

### Cretaceous Chalk

The distribution of overpressure in the Ekofisk and Tor Formations of the Chalk Group (Figure 4) is also related to the distribution of the overlying Palaeocene sandstones. Where the sandstones are thick and free-draining in the north of the Graben, the upper Chalk formations can expel fluids, and so remain hydro pressured. Where the Palaeocene sandstones are thin and discontinuous (and thus over pressured, as in well 29/10-2) or absent entirely (in which case the Chalk is overlain directly by over pressured Tertiary shales), vertical fluid flow in the upper Chalk is restricted and the Ekofisk and Tor Formations are over pressured.

Rising pressures at the base of the Chalk Group (Hod, Herring and Flounder Formations) suggest restricted fluid flow and lower formation permeability due to the muddy nature of the lower Chalk. Mudstone and marl strata form partial barriers to fluid flow.

### Lower Cretaceous–Triassic

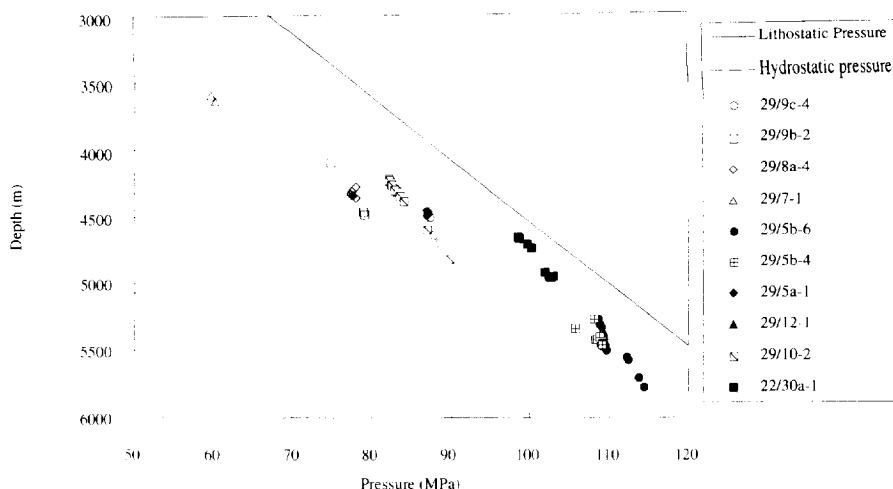
The pressure distribution in the sedimentary rocks that lie below the Cretaceous Chalk is complex. This complexity lends itself to examination at a range of scales: the basin-scale (tens of kilometres); at the scale of individual fault blocks (5–10 kilometres), a suitable scale for discussing the definition of pressure cells; or at the scale of reservoirs (100 m), a suitable scale of observation for a discussion of pressure seals.

### Basin-scale: control by structure

The pre-Cretaceous structural geology of the basin exerts a principal control on the magnitude and distribution of overpressure. The large-scale control of structure on overpressure is shown by Figure 5. The Western Platform, with relatively shallow pre-Cretaceous reservoirs and good lateral connectivity, is hydro pressured. Overpressure increases into the deep centre of the basin. The lower over pressures developed in the south of the study region suggest improved connectivity to the Platform, possibly due to permeable basin-margin faults (Cayley, 1987). A similar distribution has been noted for the Northern North Sea (Buhrig, 1989). The increased coverage of pressure data available to this study confirms the broad distribution of pressure described by Cayley (1987) and Gaarenstroom *et al.* (1993).

### Block-scale: pressure cells

RFT measurements allowed us to divide the pre-Cretaceous sandstones of the region into pressure cells on the basis of differing pressure–depth gradients. The East Forties Basin (Figure 10) contains three distinct pressure cells. Several wells in the Basin penetrate one cell on a central fault terrace. A shallower cell on the axial Forties–Montrose High (forming the western edge of the East Forties Basin, penetrated by well 30/1c-2) is differentiated from the terrace cell by a parallel gradient at an overpressure that is approximately 2 MPa lower. The eastern margin of the East Forties Basin forms a third cell (penetrated by well 23 27-6), which despite similar depths of 4000 m to the axial High is at a far lower overpressure.

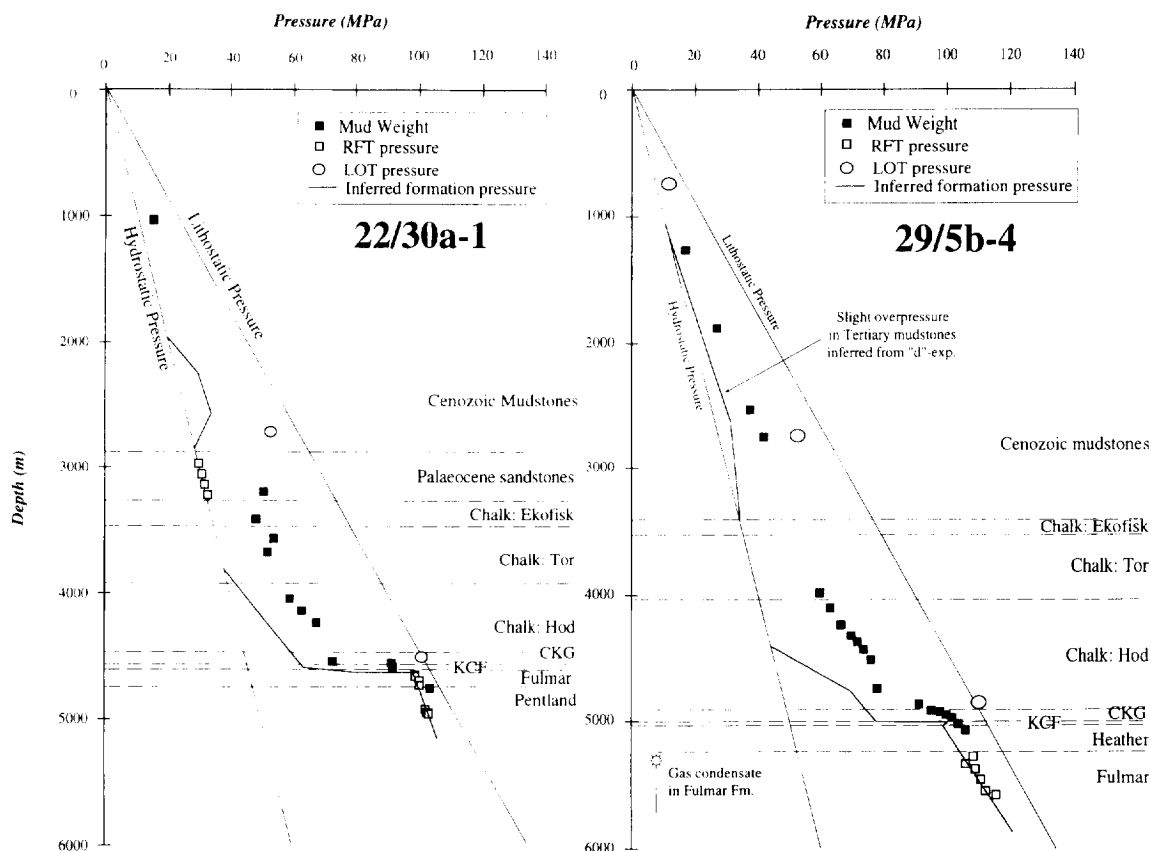


**Figure 6** Pressure–depth plot of RFTs in Jurassic sandstones in the Central Graben. The sandstones are highly overpressured, with pressures approaching the lithostatic gradient. The presence of numerous parallel pressure gradients suggest that the sandstones are compartmentalised into pressure cells. Leak Points, where the Jurassic sandstone reservoir is at higher pressure than the overlying caprock, are water-wet (open symbols). Adjacent terraces, which have the potential to leak fluid laterally towards leak points, contain hydrocarbons (closed symbols)

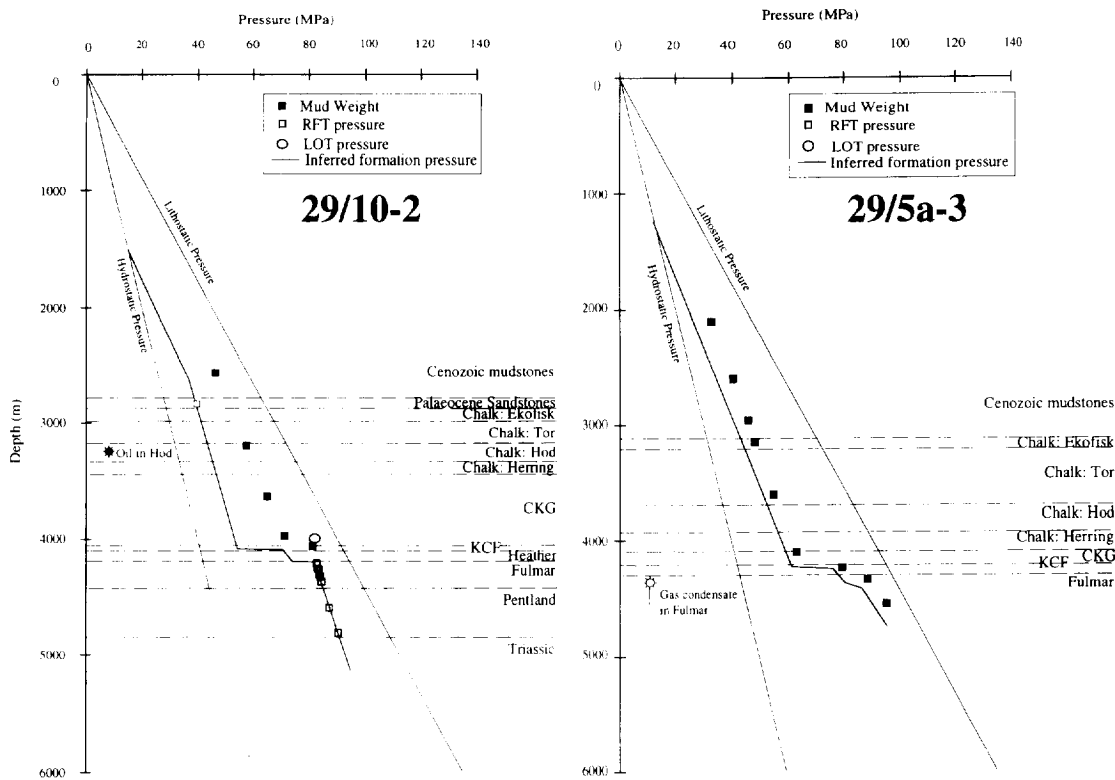
One large pressure cell may be defined in the blocks 22 30-29 5 region of the Central Graben (Figure 11), where pressure measurements in the Fulmar sandstones of well 22 30a-1 and well 29 5b-4 (in which the sandstone is 500m deeper) form a common pressure gradient, and so are in pressure communication within a pressure cell. Other cells can be defined using the same method in the

northeast of the study area on the Jaeren High (Figure 12); on the Forties–Montrose High (Figure 13); and in the south of the Central Graben in Quadrant 30 (Figure 14).

Figure 14 clearly demonstrates how the basin is compartmentalised, and the dependency of the magnitude of pressure within each cell on structural position and



**Figure 7** (A) Pressure–depth plot of well 22/30a-1. This well is sited on the crest of the Forties–Montrose High. Overpressure is inferred for the Cenozoic mudstones below 2000 m. A regression to hydrostatic pressure occurs in the Palaeocene sandstones. Pressure begins to rise again in the muddy base of the Chalk Group. The Jurassic sandstones are extremely overpressured, with pressures approaching the minimum stress. The Jurassic sandstones are at higher pressure than the overlying mudstones. (B) Pressure–depth plot of well 29/5b-4. This well is located on a fault terrace adjacent to the Forties–Montrose High. Overpressure is inferred for the Cenozoic mudstones and for the base of the Chalk Group. Pressure shows a sharp increase in the Kimmeridge Clay Fm, which exhibits the highest overpressure in the well. Gas levels show a reduction below the Kimmeridge Clay Fm



**Figure 8** (A) Pressure–depth plot of well 29/10-2. This well is located on a horst on the western edge of the Graben. Cenozoic mudstones, Palaeocene sandstones and the Chalk Group are overpressured. A sharp pressure increase occurs in the Kimmeridge Clay Fm and at the top of the Jurassic sandstones. The Jurassic sandstones are at higher pressure than the overlying mudstones. (B) Pressure–depth plot of well 29/5a-3. Overpressure is inferred for the Cenozoic mudstones and Cretaceous Chalk in this well. A sharp rise in pressure occurs in the Kimmeridge Clay Fm., marking the top of the pressure cell. Constant gradients are maintained through the upper section of the Jurassic sandstone, although a rise in pressure occurs below intraformational mudstones

geographic location. Cells on the western terraces of the Graben exhibit similar levels of overpressure regardless of depth. In contrast, cells on the axial horst are much more highly overpressured for the same depth, and the level of overpressure increases northwards along the horst in Quadrant 30.

Although data is sparse in some areas of the Graben, we have mapped the distribution of these pressure cells (Figure 15). As pressure cells are defined from well information, the lateral extent of any one cell must be interpretative. We suggest that pre-Cretaceous fault blocks control the division of the basin's hydrogeological systems into pressure cells. Pressure cell distribution follows the NW–SE structural grain of the Graben. Cells extend 20 km NW–SE and 10 km SW–NE on the Graben margins. Each fault block in the Graben appears to contain a separate pressure cell, and the bounding faults to each block form the lateral seals to cells (Figure 15). The NW–SE boundaries to cells are hypothesised to be the sedimentological boundaries to the laterally-discontinuous pre-Cretaceous sandstones, which pass laterally into siltstones (Roberts *et al.*, 1990). These NW–SE boundaries are poorly defined.

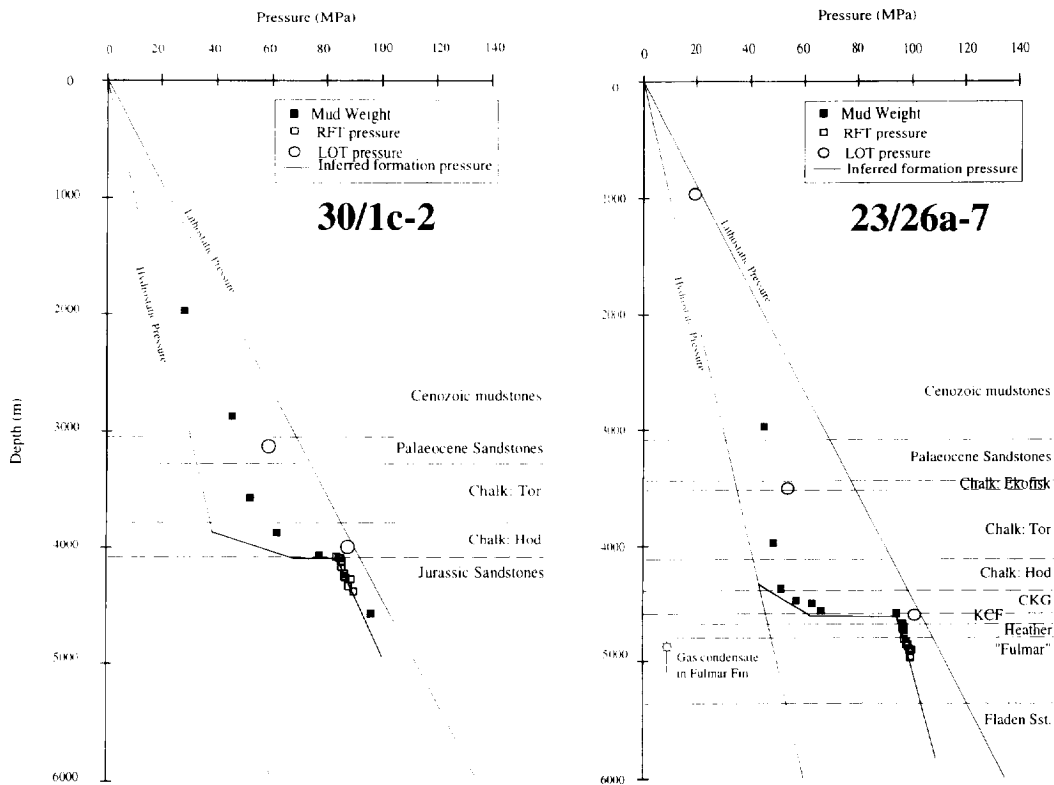
Fluid pressure within a pressure cell increases with increasing depth of the cell, and so pressures are higher in the axes of the Graben. Significant departures from this depth-dependent overpressure trend in the Graben occur in wells penetrating the axial Forties Montrose High (Figure 7a and Figure 9a). These structurally-elevated pre-Cretaceous pressure cells are anomalously highly overpressured, and exhibit fluid pressures at or close to LOT measurements of minimum stress (e.g. well

30 1c-2, Figure 9a). The thinness or complete absence of the Lower Cretaceous Jurassic mudstone aquitard on the Forties Montrose High (Roberts *et al.*, 1990) makes this anomaly even more significant. We present a model below that explains this seemingly anomalous distribution of overpressure.

#### Pressure seals

The detailed description of pressure distribution presented above allows insight into the pressure distribution at a 100 m scale. This detailed scale of observation allows us to discuss the position of pressure seals within the regional aquitards. The analysis reveals that:

1. Pressure seals are located in low-permeability lithologies. Pressure increases occur in the argillaceous base of the Chalk Group (e.g. Figure 8a), the Kimmeridge Clay Fm (e.g. Figure 7b), and the top of the Fulmar sandstone (e.g. Figure 9a). Pressure increases also occur below intraformational mudstones in the Fulmar Fm. (Figure 8b). A lithostratigraphic control is evident.
2. Pressure seals do not occur at any single, specific stratigraphic horizon. Although rapid increases in pressure may occur at the top (Figure 7b), or base (Figure 8b) of the Kimmeridge Clay Formation, increases in pressure can also occur at the top of the permeable pre-Cretaceous sandstone (e.g. Figure 7a). This variability in seal position occurs within single pressure cells (such as the cell penetrated by wells 22/30a-1 and 29.5b-4), as well as between pressure cells (e.g. between cells penetrated by well 30/1c-2 and 23/26a-7).

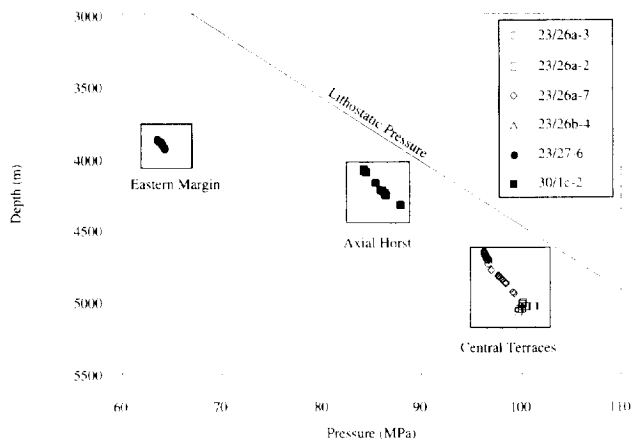


**Figure 9** (A) Pressure–depth plot of well 30/1c-2. This well is sited on the crest of the axial Forties–Montrose High, where the Jurassic is relatively shallow and the Jurassic mudstones are absent. Despite these conditions, pressure begins to rise in the muddy base of the Chalk Group and the Jurassic sandstones are extremely overpressured. Pressures approach the minimum stress at the top of the Jurassic sandstones. The Jurassic sandstones are at considerably higher pressure than the overlying muddy chalk. (B) Pressure–depth plot of well 23/26a-7. This well is located in the East Forties Basin, on a fault terrace adjacent to the Forties–Montrose High. Pressure shows a sharp increase in the Kimmeridge Clay Fm, which marks the top of the Jurassic pressure cell. Mudweight is extremely close to formation pressure in the Kimmeridge Clay Fm. A constant pressure gradient is maintained in the Jurassic section. The Jurassic sandstones are at equal pressure to the overlying mudstones due to the buoyant pressure of a gas condensate column

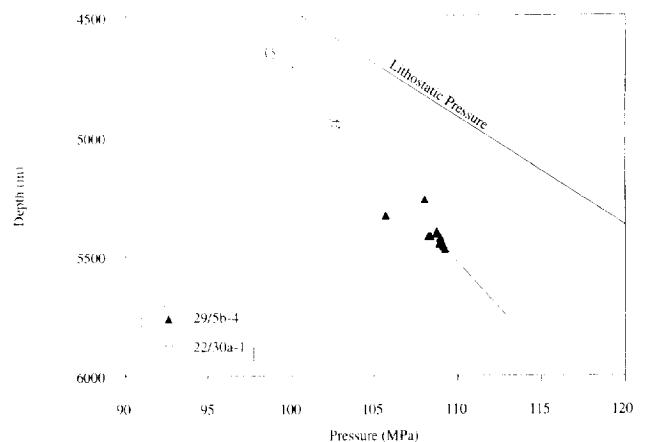
3. A link to the geochemical processes of hydrocarbon generation is suggested by the coincidence of changes in pressure gradient and the Kimmeridge Clay source rock. The Kimmeridge Clay Fm. often contains the highest overpressures developed in a well (e.g. *Figure 7b*).
4. Pressure seals occur at a range of depths. A sharp rise in pressure from 60 MPa to 80 MPa is noted at the

top of the Fulmar sandstone at 4100 m for well 30/1c-2 (*Figure 9a*). In contrast a transition from 60 MPa to 100 MPa is noted at the top of the Fulmar sandstone at 4500 m for well 22/30a-1 (*Figure 7a*). This suggests that pressure seal location is not controlled solely by depth-dependent processes. A link to stratigraphy is more strongly indicated.

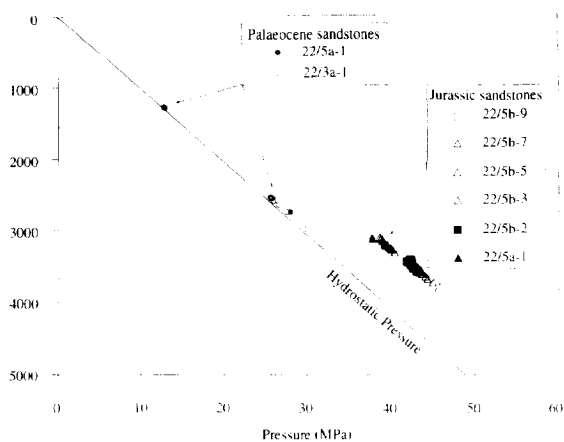
The range of depths at which pressure seals occur in the Central Graben demonstrates that pressure seals in the



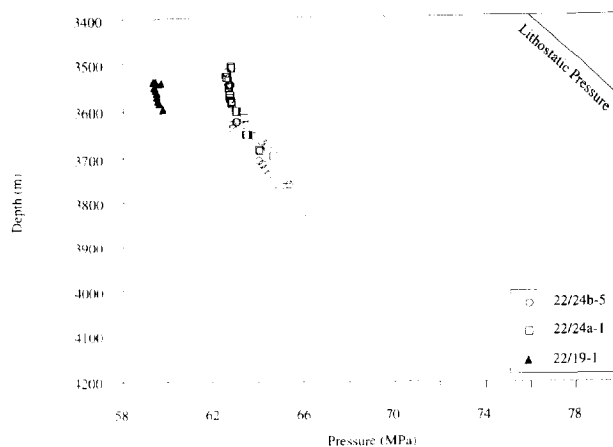
**Figure 10** Pressure cells in the East Forties Basin. Three distinct cells may be defined on the basis of common RFT pressure–depth gradients. A highly overpressured cell exists on the axial horst. Adjoining terraces are also highly overpressured. The eastern margin of the Graben contains a cell which is less highly overpressured despite similar depths



**Figure 11** A pressure cell in the centre of the Graben. Well 22/30a-1 on the crest of the axial Forties–Montrose High exhibits identical gradient to the deeper terrace penetrated by well 29/5b-4. We infer that the shallow structure is in pressure communication with the deeper terrace



**Figure 12** A pressure cell on the Jaeren High. Jurassic sandstones on a fault block on the Jaeren High in the north-east of the Central Graben form a distinct pressure cell, isolated from the overlying hydropressured Palaeocene sandstones



**Figure 13** Pressure cells on the northern Forties-Montrose High. Triassic sandstones are compartmentalised into two distinct pressure cells. A cell penetrated by wells 22/24a-1 and 22/24b-5 are isolated from an adjacent fault block penetrated by well 22/19-1

region are not planar, horizontal zones that occur at constant depths across the region. Accordingly, geochemical-diagenetic models of pressure seals (Hunt, 1990) which emphasise the control of depth and temperature on pressure seal position are inapplicable to this basin. A lithostratigraphical control on pressures is preferred. Pressure seals are directly associated with low-permeability lithologies. This provides an indication that the 'static' paradigm of overpressure (Hunt, 1990) is unsuitable for this basin. A prime tenet of the 'static' model—the presence of horizontal seals—is refuted. The 'dynamic' model (Bredehoeft *et al.*, 1994; Neuzil, 1995) suggests that fluid flow is retarded by low-permeability lithologies. On the basis of the data presented above, the 'dynamic' model is preferred in the Central North Sea.

### Central North Sea overpressure: a hydrodynamic system

The discussion presented above showed that the 'static' model of overpressure (Powley, 1990; Hunt, 1990) does not adequately describe the magnitude of overpressure in the Central Graben, or the position of pressure seals.

In this section we suggest that viewing the basin as a dynamic hydrogeological system (Bredehoeft *et al.*, 1994; Neuzil, 1995) accounts for the phenomena observed.

### Potential energy of fluids in the Central North Sea

To examine this dynamic hydrogeological system, we have recast the distribution of pressure in the study area in terms of fluid potential energy (Dahlberg, 1982). Hydraulic head ( $H_w$ ) was calculated from formation pressure ( $P_f$ ) in the water phase as:

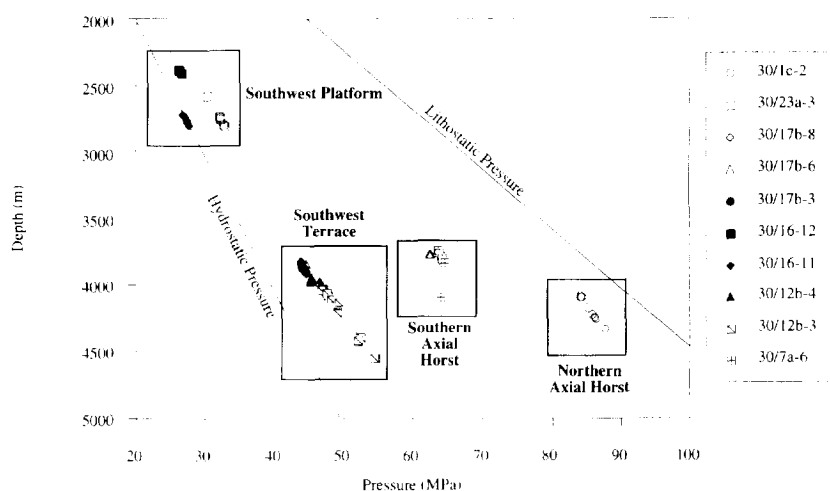
$$H_w = Z + \frac{P_f}{D_w \cdot g}$$

where  $Z$  is depth below sea level,  $g$  is acceleration due to gravity, and  $D_w$  is density of saline water. Head is related to the fluid potential energy ( $\Phi$ ) by:

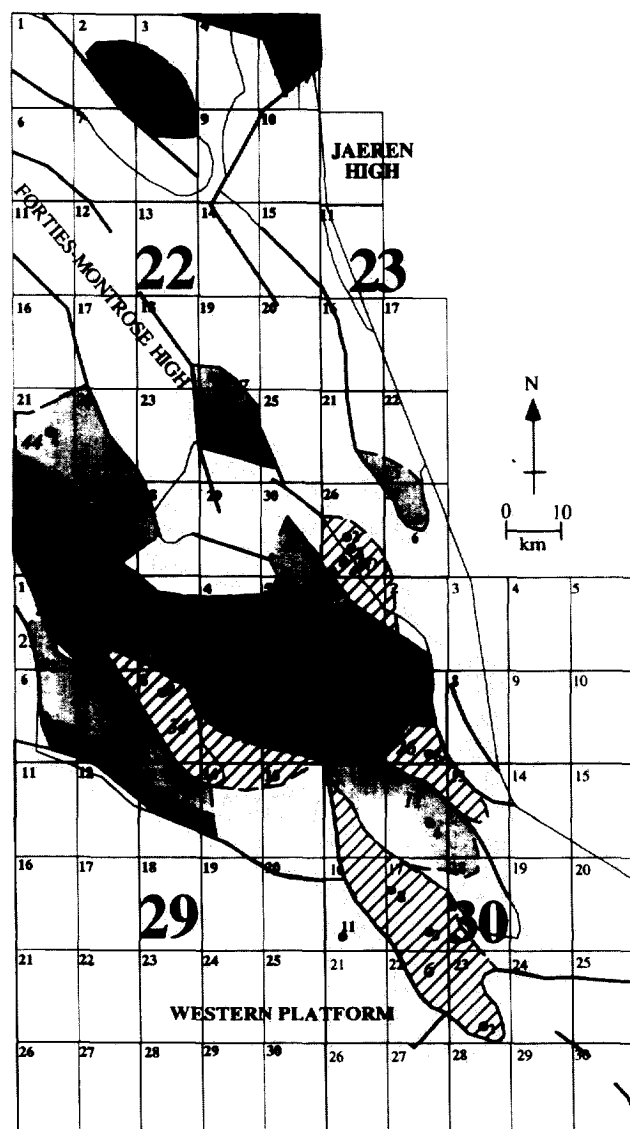
$$\Phi = g \cdot H_w$$

so that

$$\Phi = g \cdot Z + \frac{P_f}{D_w}$$



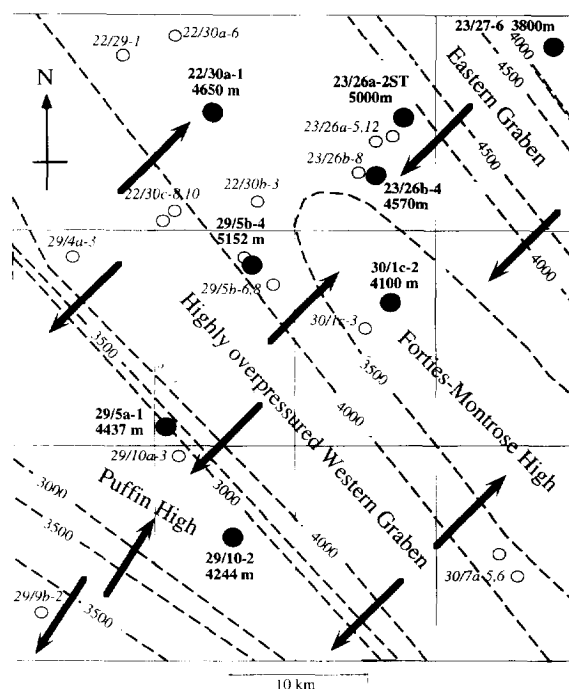
**Figure 14** Pressure cells in the Quadrant 30. This graph illustrates four cells in the south of the Central Graben. The influence of structural position in the Graben is clearly illustrated. Jurassic sandstones on the shallow Southwest Platform are hydropressured. Overpressure increases towards the axial horst in the centre of the Graben, and also increases northward along the strike of the horst. The three deep cells in this plot are all at similar depths. Accordingly, overpressure depends more closely on structural position in the Graben than on depth



**Figure 15** Map of pressure cells in the Central Graben. Italic figures denote magnitude of overpressure in each cell. Solid numbers denote well number and block number. On the basis of available data, 18 pressure cells can be delineated in the Central Graben. The NW-SE trending boundaries to pressure cells are inferred to be faults. NE-SW trending boundaries are poorly defined, and are hypothesised to be lateral sedimentary discontinuity of the Fulmar sandstones as they pass laterally into mudstones of the Heather Fm. The compartmentalisation of the Central Graben's hydrogeology reflects the complexity of the basin's syn-rift structure

As is conventional, hydraulic head was used as an approximation for fluid potential to construct a potentiometric surface (Figure 16). A necessary assumption was that there are no lateral variations in salinity due to the paucity of formation water data in the region. This assumption may be incorrect; however it is justified as the variations in levels of overpressure in the region greatly outweigh the influence of likely variations in salinity (Gran *et al.*, 1992) in the calculation of fluid potential. Moreover, fluid pressure gradients in the water legs of Jurassic reservoirs are parallel, suggesting similar salinities in the strata on which Figure 16 is based.

The potentiometric map (Figure 16) demonstrated that the distribution of fluid potential energy appears to coincide areally with structural features. Importantly, the



**Figure 16** Potentiometric map of the central section of the Central Graben. Released wells used in construction of the map are shown as a large solid circle, and are marked with well number and depth to Jurassic sandstone. Confidential wells are shown as a small open circle with well number; these are shown for corroboration only. Contours show hydraulic head in metres at top sandstone. Contours are drawn on the basis of data from released wells and contour position is interpretative. Gradients in SW and NE are inferred from the presence of low overpressures on the shelf regions (Figure 5). Datum is sea level. For reference, hydro pressured sandstones would have a hydraulic head equal to zero. Flow may be directed towards the margins of the Graben or towards the axial horsts

map revealed the presence of important lateral energy gradients. The shallow Graben margins are zones of low potential energy, whilst the western and eastern Graben axes are zones of high potential energy. Consequently, strong potentiometric gradients exist from the Graben centre onto the southwest and northeast flanks. This pattern of energy is common in actively subsiding sedimentary basins (Magara, 1968). If fluid connectivity exists between the Graben centres and the Graben margins, then this potential can drive lateral fluid flow, allowing fluid to be expelled onto the basin margins as the basin dewater. Additional unexpected zones of low potential energy in the Central Graben are represented by the axial Forties-Montrose High and marginal 'Puffin' horst. The presence of these zones is crucial to our interpretation of the basin hydrogeology.

The potential energy of the Jurassic sandstones increases with increasing depth; thus fluid potential follows the Jurassic structure of the Graben. As structures such as those penetrated by wells 22/30a-1 and 30/1c-2 on the axial high have three-dimensional hydrocarbon-trapping closure (Roberts *et al.*, 1990), it is likely that structurally closed zones of low potential energy exist along the strike of the axial horst. The marginal horst block termed the 'Puffin High', penetrated by well 29/10-2, is similarly inferred to be a closed zone of low potential energy since the sub-Cretaceous rocks of the block deepen away from the well in all directions (Gaarenstroom *et al.*, 1993). The presence of closed potentiometric 'lows' on

the axial horsts suggests that fluid escapes through the regional pressure seal at specific points (Dahlberg, 1982).

*Inter-cell and intra-cell flow in pre-Cretaceous rocks*

Figure 16 demonstrates that there is the potential for significant lateral fluid flow, beneath the regional pressure seal. The fluids in the sub-Cretaceous strata of the basin are out of equilibrium, and will seek to re-equilibrate at the stable, low-energy state of hydrostatic pressure. This re-equilibration will occur by flow, if it is possible, vertically towards the surface or laterally along potentiometric gradients such as those defined in Figure 16. The presence of potentiometric gradients implies a disequilibrium situation. This implies that either: (a) fluid flow is restricted so that no re-equilibration can occur—the impermeable seal-bounded pressure cell model (Hunt, 1990); or (b) that the cause of the disequilibrium is acting at a faster rate than the re-equilibrating flow (Neuzil, 1995). Mudford *et al.* (1991) demonstrate that in the Central Graben the rate of re-equilibrating fluid flow is too slow to allow free compaction of the sediments during the rapid Cenozoic subsidence. This leads to overpressure due to disequilibrium compaction (Mudford *et al.*, 1991). We do not address the causes of overpressure in this paper. It is sufficient to note that both possibilities (a) and (b) are tenable in the Central Graben.

The potentiometric map shows that the crests of the horsts are in energy equilibrium with deeper, off-structure regions (as in the case of wells 22/30a-1 and 29/5b-4). This implies that a hydraulic connection exists between the Fulmar sandstones of the deeper terrace (well 29/5b-4) and the Fulmar sandstones of the structurally-elevated crest (well 22/30a-1). The internal permeability of the cell must be sufficiently high to permit free fluid flow and equilibration of overpressure. Hydraulic connectivity and equilibration of fluid potential energy within a cell will elevate the pressures in the sandstone on the crest of the structure. Thus a hydraulic connection to deeper, highly-overpressured regions provides an explanation for the high pressures in the horsts (Figure 17).

In contrast, well 30/1c-2 on the Forties Montrose High suggests a different scenario. The horst is not part of the same pressure cell as the neighbouring terrace in the East Forties Basin penetrated by wells 23/26b-4, 23/26a-7 and 23/26a-2. The two structures are separated by 2 MPa pressure. Accordingly, no hydraulic connection exists between deep regions of the Graben and the shallow crest of the horst. The permeability of the Humber Group must be too low (either due to faulting or lateral discontinuity of the Fulmar sandstone) to permit free equilibration between the structures. Two possible situations exist. Either (a) the pressure cell containing well 30/1c-2 and the pressure cell containing well 23/26b-4 are totally isolated; or (b) the two cells are separated by a permeability restriction that can allow slow flow between the cells. The pressure information alone cannot differentiate between these two possibilities.

If well 30/1c-2 is isolated from the rest of the Graben, it is possible to rationalise the high pressures encountered in this well by considering the structure of the Forties-Montrose High. The High dips steeply eastward (Figure 1) and thus the Jurassic sandstone will deepen rapidly towards the East Forties Basin. Thus a hydraulic connection between the crest of the High and deeper, highly-

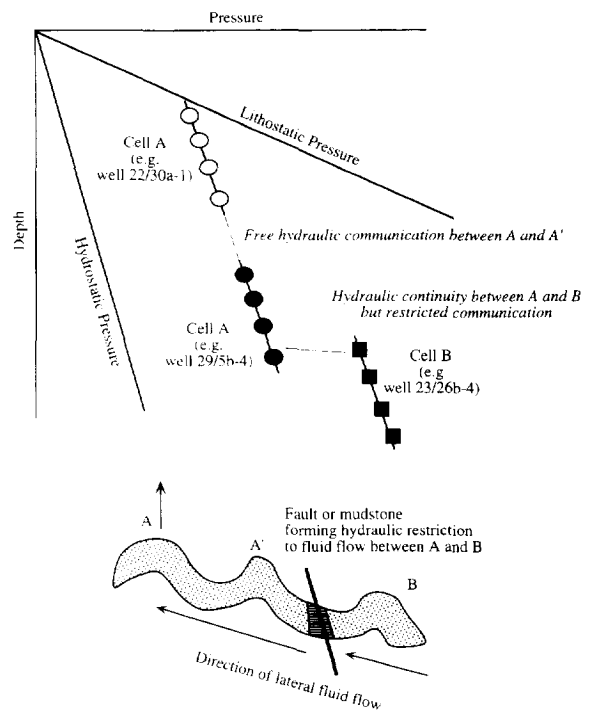


Figure 17 Cartoon of hydraulic continuity and resulting pressure-depth relationships in the Central Graben

overpressured regions may be assumed. This accounts for the overpressure in the well in a similar manner to that demonstrated for wells 22/30a-1 and 29/5b-4.

The second possibility is intriguing. Figure 16 shows that hydrodynamic potential energy conditions exist between well 23/26b-4 on the terrace and well 30/1c-2 on the horst. If the basin is viewed as a hydraulically-continuous system (Neuzil, 1995), re-equilibrating fluid flow will occur between terrace and horst if the lateral permeability of the region is non-zero. This model provides an explanation for the high pressures (close to minimum stress) in the shallow sandstones on the horst, and the lowered pressures (distal from minimum stress) in the deeper terraces.

The potentiometric map (Figure 16) reveals that the horsts are zones of low potential energy in spite of the proximity of formation pressures in the horsts to the minimum stress (as derived from LOTs). The potential for flow into the horsts is due to the structural environment, and the generation of overpressure in the deep mudstone-dominated grabens. Thus it is possible to raise pressures in the sub-seal sandstones to the minimum stress, and thus to hydraulically fracture the seal. This structurally-mediated fluid flow accounts for the lack of correspondence between magnitude of overpressure and depth. It also describes the lack of correspondence between magnitude of overpressure and seal thickness. Hydraulic connectivity between sandstones at varying depths accounts for the high pressures observed in sandstones on the axial horsts.

*Pressure seals in the dynamic model*

The dynamic model of fluid flow presented above also allows insight into the detailed morphology of pressure-depth profiles. We identified rapid rises in formation pressure associated with the KCF, or at the top of the permeable sub-seal sandstone. The pattern of inter-cell and

intra-cell fluid flow suggested above allows a pattern to be imposed on the complex, small-scale pressure distribution. Permeable Jurassic sandstones in structurally-elevated positions were suggested to possess a hydraulic connection to deeper regions. Fluid flow from deep to shallow regions in the permeable sandstones increases pressure in the sandstones on the shallow structures. Thus pressure in the sandstone will be increased to levels in excess of the pressure in the overlying mudstones. Accordingly, wells on the crest of fault blocks in the Central Graben exhibit rapid rises in pressure at the top of the permeable sandstone. This situation is exhibited by wells 22/30a-1 (*Figure 7a*), 29/10-2 (*Figure 8a*), and 30/1c-2 (*Figure 9a*).

In contrast, sandstones in deep terraces that have the potential to 'leak' fluid laterally up-dip exhibit lowered pressures in the sandstone. Wells drilled in this position encounter high pressure within the Kimmeridge Clay Fm (wells 29/5b-4, *Figure 7b*; 29/5a-3, *Figure 8b*; and 23/26a-7, *Figure 9b*). Jurassic sandstones are at a similar pressure to the overlying mudstones. Overpressures in the Kimmeridge Clay Fm. may be higher than overpressures in the underlying sandstone (e.g. well 29/5b-4, *Figure 7b*). We suggest that this distribution of fluid pressure will inhibit vertical flow through the Kimmeridge Clay seal, and that lateral flow beneath the Kimmeridge Clay pressure seal is significant. High pressures within the Kimmeridge Clay Fm. may be attributed to the generation of gas (Cornford, 1994). This produces a large fluid volume increase (Ungerer *et al.*, 1981) and is suggested to cause overpressuring in many basins world-wide (Hunt, 1990).

Thus our model of structurally-controlled flow in a hydraulically-continuous medium allows explanation of the distribution of overpressure on both a basin-scale (describing magnitude of pressure in pressure cells) and on a reservoir-scale (describing the distribution of pressure seals).

#### *Vertical fluid flow through the pressure seal: leak points*

The presence of closed or partially-closed potentiometric lows on isolated intragraben horsts (*Figure 16*) suggests that fluid can move laterally out of these areas. Fluid must escape vertically at these points. If pressures in the sub-seal permeable sandstones in structurally-high regions are higher than the pressures in the overlying aquitard, vertical fluid flow may occur through the seal. Pressures may approach the minimum stress, and hydraulic fracturing may be induced. Most importantly, erosion or non-deposition of Lower Cretaceous–Jurassic sediments on the horsts (Roberts *et al.*, 1990) has resulted in thin accumulations of the regional shale aquitard (*Figure 7a* and *Figure 9a*). Accordingly, the regional aquitard will constitute less of a barrier to vertical fluid flow on the horsts than in adjacent Graben regions.

These three structurally-related phenomena (potentiometric lows, high sandstone fluid pressures and thin seals) indicate that vertical fluid flow is localised at structurally-elevated zones. These zones are termed 'Leak Points'. Leak Points are of great significance to the hydrogeology and palaeo-hydrogeology of the region and are discussed in more detail below.

#### *Additional supportive evidence for the dynamic model*

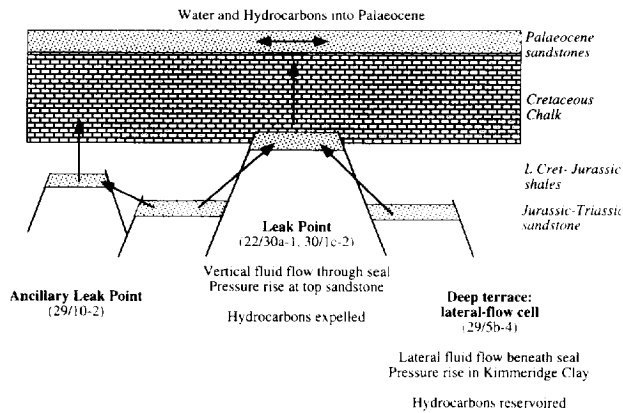
The observed distribution of pressure is explained by the 'Leak Point' model. However, a consideration of pressure

distribution can only describe the potential for fluid flow. It does not imply automatically that this fluid flow does occur. Lateral permeability restrictions may mitigate against flow. We examined other facets of the basin hydrogeology for supporting evidence. Movement of fluid in a sedimentary basin may alter the distribution of heat in the region (Garven and Freeze, 1984). The temperature pattern in the Central Graben has been examined by Andrews-Speed *et al.* (1984), who detect a  $20 \text{ MW m}^{-2}$  heat-flow anomaly in the Cretaceous Chalk above the axial horsts. Andrews-Speed *et al.* (1984) suggest that this anomaly is due to advection by fluid movement at the present day or in the geologically-recent past. Andrews-Speed *et al.* (1984) discounted compaction-driven flow due to the extremely low fluid velocities normally inferred for this fluid-flow mechanism, and preferred advection due to topographic drive or thermal convection. Our analysis of the overpressure distribution suggested a third mechanism for this fluid flow. Vertical fluid flow through the pressure seal above the Forties–Montrose High has been suggested by the distribution of overpressure. The dynamic, episodic nature of pressure-driven fluid flow (where large volumes of fluid may be expelled rapidly along pressure-induced fractures) may account for the magnitude of the heat flow anomaly. The distribution of heat flow with depth in well 30/2-1 on the central section of the axial horst (Andrews-Speed *et al.*, 1984), where the horst is adjacent to highly overpressured regions of the Graben is strongly suggestive of vertical fluid flow.

#### **Implications for hydrocarbon migration and entrapment**

The Fulmar Fm. in Leak Point wells 22/30a-1 and 29/10-2 is water-wet at the present day. The presence of bitumen (up to 20% of the rock volume, Wilkinson *et al.*, 1994) in these reservoirs suggests that these wells were hydrocarbon-bearing in the past. Wells 29/5b-4 (the Franklin field) 29/5a-3 (the Puffin field), 23/26a-3, 23/26a-7 (the Erskine-Machar fields) and 22/24a-1 (the Marnock field) contain gas condensate. We hypothesise that the pressure regime of the Graben influences the entrapment of hydrocarbons.

When hydrocarbon distribution is plotted on a pressure–depth plot of the study wells (*Figure 6*), it can be seen that Leak Points are water-wet, or contain short gas columns which are implied to be dynamically leaking. Sandstones with the potential to transfer pressure laterally towards a neighbouring leak point are hydrocarbon-bearing. Leak Points, with higher pressures in the sub-seal sandstones than in the seal itself, form an unfavourable trapping configuration. Additionally, seal failure by hydraulic fracturing, which is implied to preferentially occur at Leak Points, will also mitigate against retention of hydrocarbons. In contrast, it is suggested that the high pressures in the Kimmeridge Clay Formation overlying the Fulmar Fm. in deep fault terraces (e.g. *Figure 7b*) form a highly efficient seal to vertical leakage of hydrocarbons. The low permeability of the caprocks to hydrocarbon accumulations requires that migrating hydrocarbons must overcome a capillary entry pressure (a positive pressure differential between reservoir and seal) to flow through the caprock. If pressures in the Kimmeridge Clay Fm are greater than pressures in



**Figure 18** Summary cartoon of Central North Sea overpressure. Fluid flow between deep sandstones and sandstones on shallow structures increases pressure in the shallow structures. Pressures in these structures may approach the minimum stress. High pressures, possible hydraulic fracturing, and thin Cretaceous–Jurassic mudstones on the axial horst combine to favour vertical fluid flow through the pressure seal at these points

the reservoir, as occurs in lateral-flow cells, flow cannot occur.

### Summary

Overpressure in the Central North Sea is primarily controlled by structure. The influence of the structure of the region extends from the basin-scale to the scale of individual reservoirs. It controls the magnitude and distribution of overpressure, and the location of pressure seals (Figure 18).

A regional aquitard is formed by Cretaceous chalks and Cretaceous Jurassic mudstones. In the north of the study area, the basin-wide permeable sheet of the Palaeocene sandstones overlying the aquitard drains the basin, remaining hydropressed and allowing the Cretaceous Chalk to dewater freely. To the south of the region, this aquifer becomes thin and overpressured, leading to overpressure in the upper Chalk.

Below the regional aquitard, extremely high overpressures are developed in deep Jurassic and Triassic sandstones. These strata are divided into pressure cells. Pressure cells on the crests of the axial horsts exhibit extreme overpressures in permeable sandstones. The magnitude of fluid pressure is close to the minimum stress. The sandstones are at much higher overpressure than the overlying mudstones. In contrast, sandstones in deeper cells, on the flanks of the axial horsts, exhibit sandstone fluid overpressures significantly less than the minimum stress. Sandstone pressures in these cells are less than or equal to overpressures in overlying mudstones.

High pressures in sandstones in structurally-elevated positions can be attributed to hydraulic communication with deeper regions. Fluid flow between deep regions and elevated regions has increased pressure in the shallow structures. In contrast, the deeper cells have lowered pressures in the permeable sandstones due to lateral leakage. These cells exhibit high pressures in the Kimmeridge Clay Fm., which forms the upper pressure seal to the deep pressure cells. The highly overpressured horsts are termed 'Leak Points', as vertical fluid flow at these points is facilitated by the relative thinness of the regional aquitard and the possibility of hydraulic fracturing of the aquitard.

The recent existence of such vertical flow is independently evidenced by heat flow anomalies.

The hydrogeology of the Central Graben is a dynamic system: the basin seeks to re-equilibrate at a stable low-energy state. Re-equilibration occurs by fluid flow. This dynamic model of fluid flow accounts for overpressure and hydrocarbon distribution in the region (Figure 18).

### Acknowledgements

DD was funded by NERC. Elf Enterprise Caledonia are thanked for access to pressure data. This work has benefited from many valuable discussions with G. Holm. J. Cartwright and an anonymous reviewer are thanked for reviewing this paper.

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