Overburden deformation patterns and mechanisms of salt diapir penetration in the Central Graben, North Sea

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Abstract

Active and passive diapirism control the deformation and geometry of hydrocarbon traps in the overburden, and a more detailed understanding of this process will help reservoir prediction and hydrocarbon recovery. Cores studies of seven Central Graben diapirs indicate Zechstein salt penetrated Late Cretaceous chalk by extreme tectonic thinning with high-angle (>70° to bedding) normal faulting, tensile fracturing and pressure solution. Attenuation of the chalk significantly weakens the overburden, allowing buoyancy forces to dome up the overburden. Doming created enough topography for downslope sliding of chalk slabs on slip planes parallel to bedding or, in the case of the Kyle diapir, for chaotic debris flows of lithified chalk. Significant extensional bedding-parallel faults and slump folds are developed within Palaeocene shale on the diapiric flanks. Inter-granular slip in unconsolidated clastic material was probably the dominant deformation mechanism. Diapirs have penetrated the Palaeocene clastic sediments by maintaining topographic relief, so that unlithified sediment continually slid off the crest, producing translated intact rafts up to several tens of metres in thickness. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

There has been a surge in salt-tectonics research in the past decade, but there has been relatively little previous work on the details of diapir penetration mechanisms through the overburden strata using field evidence. Seismic and physical modeling studies (e.g. Shultz-Ela, Jackson & Vendeville, 1993) commonly indicate marked thinning of units adjacent to, and surrounding the crest of salt diapirs, but natural attenuation mechanisms of the overburden have not been studied in detail. In order to address this problem, seven salt-diapirs have been investigated in the Central Graben of the North Sea (Fig. 1). Observations on core data through the overburden reservoirs of Cretaceous chalk, and Tertiary sandstones and shales are used to determine the nature and mechanisms of penetration through these horizons. The deformation features within the hydrocarbon reservoir units are described and related to position on the diapir and lithology. All the studied fields are currently in the development stage (Birch, Crowle, Hayes & Nash, 1998; Evans, Rorison & Sykes, 1999; Foster & Rattey, 1993), and this analysis is aimed at understanding the reservoir deformation mechanisms and patterns, to help improve hydrocarbon recovery. The study covers the Kyle and Banff diapirs in the Western Trough where salt has almost broken through the chalk; and Machar, Monan, Mungo, North and South Pierce diapirs in the Eastern Trough of the Central Graben (Davison et al., 1999, Fig. 1). The Machar diapir is overlain by chalk, but the other four diapirs in the Eastern Trough have penetrated the chalk and the Palaeocene sandstones and the reservoirs are trapped against the vertical salt stock. Two kilometers of cores...
were examined and logged from Late Cretaceous to Palaeocene chalk and Palaeocene sandstone reservoirs and shales. Broadly similar deformation patterns were found in the different diapir fields.

All the diapirs are interpreted to have grown by downbuilding from Triassic through to Palaeocene times, and were probably triggered by extensional faulting during Triassic times (Smith et al., 1993; Hosack, 1995; Davison et al., 1999). Thin (0–300 m) chalk sequences are present above the diapirs, which are surrounded by basinal areas with up to 1500 m of chalk.

Owing to the strong lithological control on the nature and intensity of overburden deformation the chalk and Palaeocene sandstones and shales are described separately. All depths referred to here, are drillers depths in metres, unless otherwise stated.

2. Deformation of chalk overburden

In the following discussion, interconnected zones of open fracturing are defined as zones where open fractures are not separated by more than 10 cm of undeformed rock, measured along the core axis. In such zones there is a high probability that all fractures will form an interconnected network in three dimensions. Fractures are classified here as tensile (Mode 1) fractures, or small normal faults with displacements usually less than 10 mm. This definition of interconnected fracture zones allows comparison of the potential hydrocarbon productivity between different rock types and positions on an individual diapir and between diapirs. The open fracture zones form laterally connected open networks on a scale much greater than core observation reveals. All thickness measurements of fractured zones noted here are measured perpendicular to the bedding dip. Natural rubble zones within the cores are due to brecciation associated with faulting, and are also noted on the logs. Details of deformation from different lithologies are now presented in the necessary detail prior to discussion of the data.
2.1. Faulting and fracturing of chalk on Banff diapir

2.1.1. Crest

The Banff diapir is elongate in a NW–SE direction parallel to a large normal fault which probably controlled its initiation (Davison et al., 1999). It is 4-km long and approximately 2.5-km wide. The southwestern flank of the diapir contains most of the hydrocarbon reserve, and the chalk and Palaeocene reservoirs have been lifted up like a flap (Evans et al., 1999, Fig. 2). Chalk from the diapiric crest (wells 29/2a-6 and 29/2a-6MST) shows evidence of pervasive minor fracturing with 46% of the core affected by open interconnected minor fractures, and 15% of the core is rubble zones associated with meso-scale (tens of meters displacement) faulting (Fig. 2). Pure dilation (Mode 1) fractures are rare, and small extensional (relative to bedding) faults are the main fracture type. The pattern of fracturing is extremely heterogeneous, with zones of intense minor fracturing up to 25–30 cm thick, developed within the fracture networks. Within such pockets, fracture density ranges between 30 and 100 fractures/m (measured parallel to the core axis). The
largest zone of interconnected fracturing is 2-m wide and is adjacent to a brecciated (rubble) fault zone of unknown displacement. The development of thicker interconnected fracture zones coupled with a typically closer spacing of fractures within zones, indicates that the Tor formation has undergone greater brittle extensional deformation than the Ekofisk formation. However, the proportions of fractured core (46%) and breccia zones (15%) remain similar in each case.

2.1.2. Shoulder

Chalk from the SW shoulder of the Banff diapir (well 29/2a-10) displays pervasive minor fracturing, comprising 40% of the core interval, coupled with brecciation zones (10% of core) (Fig. 2). Late faults with associated open fracturing cut sedimentary slumps in the chalk and bedding-parallel closed hairline fractures. Seventy-five per cent of interconnected open fracture zones have a spacing of less than 0.75

Fig. 3. (a) Cross-section and (b) map of Kyle diapir. (c)–(e) show cored zones of interconnected open fracturing (black intervals) in the chalk from two wells 29/2c-8z and 29/2c-8 and 29/2c-11. Grey shading shows zones where core was not available.
m, underlining the pervasive nature of brittle deformation. Chalk of the Tor formation is slightly less fractured, compared with the same unit adjacent to the diapiric crest (29/2a-6). On the southern diapir flank, 29/2a-7 chalk is much less affected by zones of open-connected minor fracturing (12% of core) and breccia zones (3%) (Fig. 2).

2.1.3. Lithological control on fracture systems on Banff

There are fewer interconnected fracture systems developed within minor quartz sandstone units within the Ekofisk chalk on the crest of the structure. Individual sandstone units may reach 1–2 m in thickness, with stacked sandstones up to 7 m in thickness. Ekofisk sand has in places injected into fractures up to 10-cm long in the overlying chalk. Brecciation is common within the sandstone forming polished surfaces and striae, indicating they were lithified before faulting.

2.2. Faulting and fracturing of chalk on Kyle diapir

The Kyle diapir is elongate in a NW–SE direction parallel to the regional graben trend. The diapir has a bulbous head and appears to have bulged sideways into the lower Cretaceous strata (Fig. 3).

2.2.1. Crestal breccias

Well 29/2c-8 is located SW of the Kyle diapir crest, where overburden dips steeply to the SW (Fig. 3). This well penetrated salt breccias at the top of the diapir, overlain by anhydrite breccias, followed by mixed anhydrite and chalk breccias (Fig. 4), chalk breccias, and finally intact chalk (Fig. 5). No cap rock was observed at the top of the diapir. The anhydrite clasts reach up to 1 m in diameter and are internally tightly folded and sheared indicating they originally formed part of the diapir (Fig. 4).

The salt breccias could indicate that the salt was actually exposed at the sea bed, and the salt clasts was deposited at the foot of a salt cliff. Alternatively, brecciation could have been caused by salt dissolution, such as collapse of a salt cavern roof. However, the layered nature of the breccia compositions above, and presence of matrix mud, probably indicate that this is a surface debris deposit. Rapid covering of the salt breccia would be required to preserve it from dissolution by sea water, which is possible given the nature of the overlying debris flows.

Later, anhydrite cap rock and chalk were exposed and reworked. Eventually the diapir became buried by chalk, such that only reworked chalk was involved in the debris flows.

Interconnected open fracture networks are best-developed in breccias with limestone clasts, but without anhydrite clasts. Interconnected open fracture systems in the limestone breccias affect 87% of the cored interval, compared with only 12–20% in breccias containing anhydrite clasts (Fig. 3). Anhydrite has cemented up any fractures. Fracturing within the limestone breccias constitutes the greatest proportion of open-interconnected networks of all the wells studied in the seven diapirs. Some fractures only affect individual chalk clasts, and therefore developed before the debris flow deposition. This indicates the chalk was lithified and fractured before the debris flows occurred, and implies that the diapir was able to penetrate lithified chalk sequences. Other open fractures cut across both matrix and clasts and are randomly oriented, suggesting later phases of fracturing in a protracted deformation history. The intact chalk above the debris flows is highly fractured with 83% of the core affected by randomly-oriented open networks (Fig. 6).

2.2.2. Kyle Diapir Shoulder

On the shoulder of the diapir (wells 29/2c-8z, 29/2c-11, Fig. 3) there are many bedding-parallel extensional fault zones with cm-scale displacements. It is not clear whether these are flats of listric faults, or whether they link to many small faults which are oriented at 60° to bedding, which mainly dip outward from the diapir structure. Open horsetail fractures splay off both of these types of fault zones. In well 29/2c-11, chalk
above the diapiric shoulder displays extensive minor fracturing, with zones of both interconnected open fractures and closed (calcite-filled) fractures. These fracture networks affect 12% of the cored chalk interval. Soft-sediment folding and shearing is also observed in the chalk section from 2478 m (8130 ft) to 2482.5 m (8145 ft). In well 29/2c-8z, on the southwest shoulder, 18% of the chalk section is affected by open interconnected fracture networks, which are concentrated in dolomitic mudstones.

Fig. 5. Lithological log of the Kyle well 29/2c-8 showing the systematic change in composition of the Palaeocene debris flows.
2.2.3. Western flank of Kyle diapir

The western flank of the diapir farther away from the crest (well 29/2c11y, Fig. 3(a) and (b)) contains chalk core with less than 1% affected by interconnected open fracturing. The majority of small faults were clay-filled and isolated, and numerous calcite-filled tensional veins occur at a high angle to the bedding.

In summary, chalk debris flows are the most attractive fractured reservoir unit on Kyle. There are a large number of bedding-parallel normal fault zones with cm-scale displacements, which dip outward from the diapiric crest along the SW shoulder of the diapir in unbrecciated chalk.

2.3. Faulting and fracturing of chalk on Machar diapir

The Machar salt diapir is the largest in the study area. It has an approximately circular plan view and a diameter of 4.2 km. The diapir was arrested at base chalk level, but the chalk has been very highly deformed and partially removed from the crest on the NE side (Fig. 7).

In well 23/26a-13, which lies approximately 1.6 km from the Machar crest (Fig. 7), open fractures with an average spacing of 5 cm occur along the core. Heterogeneous zones of interconnected fracturing typically reach up to 4 m in thickness (Fig. 7). The chalk within 2 km of the diapir crest is much more affected by zones of open interconnected fractures (60% of core) compared with the flanks at 2.5 km from the crest (11% of core, 23/26a-13ZA).

2.4. Faulting and fracturing of chalk on South Pierce diapir

The South Pierce diapir is elongate in an E–W direction, which is probably controlled by an underlying extensional fault (Birch et al., 1998). The diapir has

Fig. 6. Intense open fracturing in brecciated chalk from the Kyle field (1904 m in well 29/2c-8). Core diameter c. 10 cm.
Fig. 7. Cross-section of the Machar diapir showing summary core logs of zones of interconnected open fracturing and stylolite/dissolution residue seam development in the chalk. The length of the bars in the residue seam columns is proportional to the thickness of the seam.
Fig. 8. Cross-section of the South Pierce diapir. Zones of bed-parallel slip in Palaeocene mudstones and sandstones are shown as black intervals. Intensely sheared intervals reach up to 4 m in thickness.
Fig. 9. Cross-section of the North Pierce diapir. Logs indicate zones of interconnected open fracturing in black.
penetrated to 600 m below sea bed, into Pliocene strata (Fig. 8).

One well (23/27-2), which is situated approximately 1 km north of the diapir crest, recovered chalk from this field (Fig. 8). Fractures within the chalk (Ekofisk formation) in well 23/27-9 are closed and typically cemented with calcite. Thick calcite veins (up to 10 cm in width) may be then filled with calcite derived from pressure solution, as shown by local stylolites and residue seams. Thicker drusy veins filled with calcite have developed parallel to bedding at 2529 m (8289 ft) in well 23/27-9.

2.5. Faulting and fracturing of chalk on North Pierce diapir

The North Pierce diapir is the smallest diapir in the study. It is almost circular in plan view with a radius of approximately 1 km. The diapir has penetrated the chalk and Palaeocene mudstones and sandstones (Fig. 9).

Adjacent (100 m) to the sub-vertical salt wall (well 23/22a-2), heterogeneous zones of interconnected open fractures are typically less than 2 m in thickness, with 31% of the Tor formation and 15% of the Hod formation affected by open fractures (Fig. 9). Brecciation zones representing larger faults form 9% of the core. The interconnected fracture zones in the chalk have the highest density of fractures of any of the wells studied on the seven diapirs. However, many of these fractures are totally cemented with calcite.

Four hundred metres from the salt wall, the amount of interconnected open fracturing decreases to 26% of the cored interval in the Tor formation (well 23/22a-2Z). Zones of interconnected fracturing reach up to 2 m in thickness and may be separated by unfractured chalk zones up to 20 m in thickness. Bedding plane slip zones are also present in the chalk, where the bedding dip increases to 30°.

2.6. Pressure solution in the chalk

Stylolites, dissolution residue seams, and embayed chalk granules are present in all the chalk cores and indicate chalk dissolution and removal. Calcite-filled fractures represent sinks for some of the dissolved calcite, but mass balance calculations suggest much of the CaCO₃ has been entirely removed from the system and escaped to the sea bed. Dissolution features are most apparent in ‘cleaner’ chalks with a CaCO₃ content of more than 85%. Most of the stylolites and dissolution residue seams are parallel to bedding, which varies widely in dip, suggesting that pressure solution began prior to rotation. The growth of large (up to 1 cm) pyrite cubes within residue seams on Machar, North and South Pierce suggests that fluid transfer associated with mineralisation has taken place in the zone immediately adjacent to the seams.

On Banff, bedding-parallel hairline stylolites are well developed in chalk, and locally grow along pre-existent fractures. Dissolution seams up to 1 cm in thickness are developed near the base of the core in well 29/2c-8z. Peaks of the stylolites are generally oriented perpendicular to bedding, indicating maximum principal stress is also orthogonal to bedding. Zones of chalk clasts have interpenetrating contacts produced by pressure solution and suggest up to 10% volume loss.

A more detailed study of pressure solution has been undertaken on Machar. In all three studied wells (23/26a-12ST, 23/26a-13, and 23/26a-13ZA), the top of Tor formation typically contains only relatively thin dissolution residue seams with a maximum thickness of individual seams smaller than 20–30 mm (depending on the well). Below a certain depth, which is different for each well, the maximum thickness of the seams increases to 55–150 mm (Fig. 8). Seams of such thicknesses could extend over hundreds of metres or even kilometres. This is based on our observations on the southern cliff-coast of Flamborough Head, Yorkshire, UK, where 50–60 mm thick seams can be traced for over 800 m and are even continuous across normal faults with minor (<1 m) displacements.

In the chalk from Machar, the number of dissolution residue seams (>2 mm in thickness) per 10 m chalk (dip-corrected thickness) increases with depth from 2–8 (depending on the well) to 31–35 (Fig. 10(a)). The cumulative residue seam thickness increases with depth from 0.5% of the chalk in all wells to 3% in wells 23/26a-13 and 23/26a-13ZA, and to 13% in well 23/26a-12ST (Fig. 10(b)). However, comparing the figures of the different wells, it appears that there is no simple relationship between the absolute depth or the stratigraphic level (based on nanno zones) of the chalk, and values for the number, maximum and cumulative thickness of the dissolution-residue seams.

The chalk volume loss due to pressure solution along distinct surfaces (i.e. forming stylolites and pressure-solution residue seams) was determined with a geometrical method (based on measuring stylolite amplitudes), and a chemical method (based on quantification of immobile element enrichment in the residue seams). Volume loss ranges between 35 and 67%. Including an estimate of the volume loss due to intergranular pressure solution of 0–10%, we calculate a bulk rock average volume loss of 46–54%.

Volume-balance calculations of the amount of dissolved carbonate and the porosity reduction in the preserved sequence show that a considerable amount of material must have been removed from the studied chalk. The pressure solution transfer system must, therefore, have been open. A major convection system next to the diapir (c.f. Jensenius & Munksgaard, 1989)
is assumed to provide the required fluid flux to transport the carbonate out of the Machar chalk.

Pressure-solution residues from the Machar oilfield consists of phyllosilicates, calcite, quartz and rare pyrite with the phyllosilicates being mixed-layered illite/smectite, kaolinite, and minor chlorite. This mineralogy, together with a high illite crystallinity, suggest an unexpectedly high diagenetic maturity. This could be due to a temporary temperature anomaly possibly caused by hot fluids, which have ascended adjacent to the Machar diapir using faults and interconnected fractures as pathways. The implied temperature increase of approximately 100°C above regional would be too high to be simply due to the higher thermal conductivity of the salt where anomalies of only 10–20°C are predicted (Peterson & Lerche 1996).

3. Palaeocene sandstone and mudstone deformation

3.1. Deformation of the Palaeocene sandstone and mudstone on Banff diapir

The sandstone and mudstone of the Andrew and Maureen formations in well 29/2a-7 contain extensional fractures that are rarely parallel to, but more typically at 45° to bedding. Fractures at high angles to bedding define conjugate extensional systems with up to 2 cm displacement. The contact between the shale of the Maureen formation and the chalk of the underlying Ekofisk formation is marked by an increased fissility within the mudstone. Extensional fractures, oriented at 45° to bedding in the chalk, become listric and bedding parallel in the mudstone. Extensional faulting in the mudstone is typically oriented closer to the bedding than in adjacent chalk and sandstone.

Extensional fractures, infilled by calcite (up to 3-mm thick), cut bedding in sandstones at 70°. Bedding-parallel calcite-filled fractures (1-mm thick) also have ramp-flat geometries resulting in calcite-filled pull-aparts. Open fractures at high angles to bedding displace bedding-parallel calcite veins, in places contractionally.

Mudstone clasts in the sandstones are smeared into extensional faults, indicating the sandstones were not lithified when faulting initiated. Isoclinal slump folds in the Palaeocene claystones are cut by extensional fractures and calcite veins.

3.2. Deformation of Palaeocene sandstone on Machar diapir

Only 25 m of Palaeocene sandstone was cored in well 23/26a-12ST. Forty per cent of the core contains interconnected open fractures, with one zone reaching 9 m in thickness, whilst rubble and brecciation zones comprise 5% of the core (Fig. 7). Most of the fractures are extensional with respect to bedding, although bedding-parallel detachments also occur.

3.3. Deformation of Palaeocene sandstone and mudstone on South Pierce diapir

Four wells were examined on South Pierce, which all lie at distances of approximately 400 m from the diapiric wall (Fig. 8). Cores display only limited evi-

![Fig. 10. (a) Plot of number of dissolution residue seams/10 m of chalk (corrected for dip) against driller’s depth in metres for chalk cores on the Machar well 23/26a-12ST. (b) Plot of cumulative thickness of residue seams in 10 m chalk intervals (corrected for dip) against driller’s depth in metres for chalk cores on the Machar well 23/26a-12ST.](image-url)
Evidence of fracturing and minor faulting at high angles to bedding. However, bedding-parallel slip horizons with polished surfaces are very common, especially along lithological boundaries between mudstone and sandstone (Fig. 8). Bedding-parallel slip is most evident in wells 23/27-5 on the eastern flank and well 23/27-9 on the northern flank of the diapir. A zone of highly-polished slip surfaces reaches up to 1.2 m in thickness at 2777 m depth in well 23/27-5. This must represent an extensional slide zone with at least several tens of metres of slip. XRD investigation of these polished surfaces did not detect a change in clay mineralogy from the adjacent mudstone, and frictional heating was not thought to be significant.

3.4. Deformation in the Palaeocene sandstone on North Pierce diapir

Close to the diapiric wall (well 23/22a-2), 49% of the cored interval through Maureen and Andrew formation sandstones consists of interconnected fracture zones (Fig. 9). This decreases to 16% of the cored

Fig. 11. Cross-section of the Monan diapir. Logs show zones of interconnected open fracturing in black.
interval affected by interconnected open fractures in well 23/22a-2Z, which is situated approximately 400 m from the diapir wall, and 0% of the cored interval is affected in 23/22a-3 at 800 m from the diapir wall (Fig. 9). There are large amounts of soft-sediment slumping and folding close to the diapir in well 23/22a-2, which are associated with calcite veins and fluidised breccias containing siltstone clasts.

3.5. Deformation of Palaeocene sandstone and mudstone on Monan diapir

Interconnected open-fracture networks affect approximately 23% of the cored interval (80 m) of Palaeocene elastic rocks in well 22/20-4, which lies within 15 m of the vertical salt diapir (Fig. 11). Sealed fracture networks also affect 18% of the cored interval. In the upper 60 m of the cored section the open fracture networks are preferentially formed in mudstone sandwiched between sandstone layers. The fractures will provide hydraulic connection between individual sandstone bodies and enhance reservoir performance. The closed fracture systems occur in the lower 20 m of cored section, which consists of grey siltstone, light-grey wackstone, light-brown sandstone and olive-green to black mudstone. Closed fractures are mainly in the mudstones. Zones of intense shearing in the mudstone are parallel to the bedding in the adjacent sandstones (Fig. 12). Bedding plane dips in the sandstones are steeper towards the base of the cored interval, and this is probably caused by block rotation above listric extensional faults which sole out parallel to bedding (Fig. 12). Only 3.5% of the cored interval in well 22/20-4 is affected by soft sediment slumping, which occurs exclusively in mudstone (Fig. 12).

Well 22/20-2 lies about 700 m from the diapir wall (Fig. 11). The cored interval consists of Palaeocene turbidite sandstone and interbedded mudstone. The mudstone exhibits slump folding, and approximately 14% of the cored interval is occupied by slumped mudstones (Fig. 13). The sandstones do not exhibit any soft-sediment slumping features. The amount of core affected by open interconnected fracture zones is approximately 12%, and approximately 6% is affected by fault brecciation with a large fault zone present between 2810 and 2818 m (Fig. 13). In this fault zone, fracture spacing is reduced to 1 cm, with random orientations. All the faulting and tension fracturing is extensional with respect to bedding, with the exception of one small thrust fault observed at 2729.5 m.

3.6. Deformation of Palaeocene sandstones on Mungo

There is little variation in the amount of interconnected open fracturing within the cores of Palaeocene sandstones. Less than 15% of the cores is typically affected by open fracture networks. Well 23/16a-4 lies closer to the upper diapir bulb at approximately 750 m from the salt wall (Fig. 14). It has the smallest proportion of interconnected open fractures (5%), compared to 17% in well 22/20-3 at 1.5 km from the upper diapir bulb, and 14% in well 23/16a-5Y situated at 1.4 km (Fig. 14). Heterogeneous zones of open fracturing are usually less than 1 m in width. Most (>98%) of the fractures and minor faults are extensional and oriented at greater than 60° to bedding, with limited displacements of 5 mm. Conjugate extensional faults maintain angles of 60° to bedding, despite bedding having been rotated to dips of 30–40°. Local high-angle reverse faulting has apparent offsets of less than 5 mm. Bedding-parallel calcite veins (up to 12 mm in width) are developed, and bedding-parallel slip horizons are common, especially at major lithological boundaries such as the base of sandstone units. Soft-sediment folding and faulting is relatively common and may also be associated with calcite-filled tensional fractures formed on the outer arc of soft sediment folds. Deformation within massive homogenous sandstones is accommodated by mm-wide granulation seams, oriented at a high angle to bedding.

4. Discussion

4.1. How do diapirs apparently pierce large thicknesses of overburden?

The mechanism by which salt deforms overburden in nature has not previously been well documented in the literature (although see suggestions in Shultz-Ela et al., 1993, p. 279). Diapiric penetration of reservoir horizons is not produced by active salt injection. Our study of diapir heads and flanks indicates that Central Graben diapirs penetrate through the overburden by causing intense extensional faulting, tensile fracturing, and pressure solution, which drastically thin the overburden. Buoyancy forces created topographic relief of the thinned chalk, resulting in chalk sliding off the crests of the diapirs. Evidence for this mechanism is soft-sediment slump folding and bedding-parallel fault zones in the chalk. Debris flows of salt, and anhydrite on the Kyle field indicate that the salt is exposed at or near surface with topographic relief of several tens to hundreds of metres developed during the Late Cretaceous to Palaeocene period. Lithified clasts in the debris flows indicate that the chalk is indurated and cemented, but nevertheless the diapir is able to break through and shed off this lithified material.

Observations from South Pierce indicate that the bedding-plane slip surfaces, with at least 10 m of displacement, are common in the Palaeocene elastic
Fig. 12. Structural log of well 22/20-4 on the Monas diapir indicating the bedding orientations, slump folding, faults and open fracture networks.
Fig. 13. Structural log of well 22/20-2 on Monan diapir showing bedding plane orientations, zones of slump folding and interconnected fracturing.
rocks. Palaeocene sediment slid off the diapir crest, and stacked slumped sandstone horizons are produced downslope on the diapir flanks. Sliding preferentially took place along Palaeocene mudstone horizons, which show common slump folding and polished faulted surfaces. Folding is not always present in the sandstones, which ride on the slides, and sometimes the coherent blocks can translate large distances without any internal deformation. Thickness of the Tertiary sandstone packet increases from zero at the crest to 300 m on the flanks, and some of this thickening must be produced by sediment sliding off salt diapir crests. It is envisaged that build-ups of tens of metres of sediment are followed by up-doming of the salt diapir crest accompanied by faulting and rotation of the strata until a critical angle is reached, and then overburden slides off the diapir. Hence, the diapirs were close to or at the surface during the Palaeocene to Eocene period, producing bathymetric highs, so that little sediment could accumulate on their crests.

Fluid transfer in chalk cores from Banff, Machar, Kyle and North Pierce has resulted in interconnected vuggy fractures filled with calcite. This calcite is probably derived from pressure solution, but much of the dissolved chalk on Machar has been removed from the system and possibly escaped along major faults directly into the sea.

These combined effects described above produce an apparent intrusive geometry, although overburden has been tectonically thinned and removed, rather than actively injected by salt. A summary of the typical deformation patterns observed above a diapir, and a schematic Palaeogeography during the Palaeocene period are provided in Figs. 15 and 16.

Fig. 14. Cross-section of the Mungo diapir with logs of zones of interconnected open fracturing (black) in the Palaeocene sandstones and shales.
4.2. Implications for reservoir productivity

Almost all (>99%) faults and fractures observed are extensional, and form at high angles (>70°) to bedding. The greatest amount of interconnected fracturing and brecciation (natural rubble zones) in the chalk is in wells at or near the crests of the diapirs (Fig. 15). The fractures are commonly open, indicating that deformation has continued until the present day, and/or cementation has been inhibited owing to the presence of hydrocarbons, which only began to accumulate after chalk deposition. Very close to the diapir contact (<50 m), the fractures are cemented with calcite or anhydrite, which is interpreted to be due to increased fluid flow concentrated along the diapir contacts. The fracture intensity within the chalk does not vary consistently from base to top at any one position on the diapir. Reservoir productivity in the chalk will be significantly enhanced by fracture permeability on crest of the diapir structure, as the intrinsic permeability in the chalk is insufficient to sustain economic flow rates. However, the chalk is absent on parts due to non-deposition or downslope sliding (Davison et al., 1999).

Stylolite and dissolution residue seams may cause important barriers to fluid flow, which are parallel to bedding. These are made of clay minerals, and other insoluble material and they display very low permeabilities in the order of nannodarcies (N. Beveridge, 1997, personal communication). The maximum thickness, the cumulative thickness and number of residue seams increase with depth on Machar, suggesting they will also be more laterally extensive at depth on the diapir flanks. The thicker seams are also less likely to be broken by later normal faults. Our observations at Flamborough Head (UK) indicate the thicker stylolites will have surface areas greater than 0.5 km² and are therefore important at the reservoir scale (Safaricz & Davison, 1998). Liner perforation programmes in oil wells will need to make sure that bullet perforations are made just below every significant stylolite and dissolution residue seam, to ensure maximum recovery from these intervals. Interbed slip along thicker dissolution residue seams may encourage secondary faulting and fracturing at high angles to the slip planes.

Palaeocene sandstone reservoirs are not significantly affected by faulting and fracturing, except near the diapir (<50 m) where intense fracturing may be filled with calcite, and reservoir productivity will be adversely affected. Downslope sliding of the sandstones will increase reservoir thickness in the flank areas. Soft sediment folding and slumping appears to be the most abundant on the flanks, but this does not appear to affect reservoir productivity (Birch, 1998, personal communication).

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Fig. 15. Summary diagram showing deformation of chalk and Palaeocene sandstone reservoirs above a salt diapir.
In an accompanying paper (Davison et al., 1999), we demonstrate that the Central Graben diapirs have been affected by Mid-Miocene compression, which rejuvenated their growth. However, there is very little evidence of small-scale compressional features in the cores of the chalk and Palaeocene clastic rocks. Hence, small-scale deformation patterns produced above diapir crests by periods of active diapir upbuilding are essentially the same as those produced by downbuilding. Extensional faulting, producing extension of bed lengths, occurs above the salt diapirs in both cases.

5. Conclusions

1. The proportion of interconnected open fracture networks in the chalk increases towards the diapiric crests, with up to 90% of the core affected, and diminishes to <5% farther than 2 km from the crest. The spacing of open fracture zones varies more on the flanks compared to the crest of the diapir.

2. Chalk debris flows are the most highly fractured rocks encountered in this study. They will produce very large hydrocarbon flow rates.

3. Zones of open fracturing in the Palaeocene sandstones are much more restricted than in the chalk, and there is no systematic relationship between fracture intensity and position on the diapir. Zones close to the diapir (<50 m) can be very highly faulted and fractured, but the fractures can be sealed by calcite cement and reservoir quality may be poor.

4. Most (>99%) of the small normal faults and tension fractures in the chalk and Palaeocene sandstones are extensional with respect to bedding, and maintain high angles (>70°) to bedding, even on highly rotated diapir flanks. This indicates that most fractures and faults initiated before significant bedding rotation, but they continued to be active during rotation.

5. Important faults parallel to bedding planes are present in the chalk and Palaeocene clastic rocks on the flanks of the diapirs, where down-dip extension has taken place. Sliding along bedding-plane faults is most common at boundaries between sandstones.

Fig. 16. Summary cartoon of a salt dome upper surface during Palaeocene times indicating structural deformation and sedimentation features. This diagram is based on observations from all of the diapirs in the study, but most closely resembles the Kyle diapir.
and mudstones, once rotation of the bedding to an unknown critical angle has taken place. Highly-polished bedding-plane extensional slip zones up to 1.2-m thick in the Palaeocene on South Pierce and Mungo suggest at least several tens of metres of slip across these zones.

6. Chalk can be significantly thinned and achieved by pressure solution. We estimate that approximately 50% of the cored chalk interval has been dissolved on Machar, to produce bedding-parallel dissolution residue seams up to 15 cm in thickness. These will be laterally extensive fluid flow barriers, unless cut by faults with several meters of throw. The dissolved chalk has partially occluded the pore spaces, and local reprecipitation resulted in abundant calcite veins and cemented faults. However, much of the dissolved chalk must have been carried up into the Tertiary elasic overburden, and possibly to the sea bed.

7. Closed fracture networks increase toward the diapiric crests and the contact with the salt diapirs. These are most intensely developed in the Chalk group. Increased fluid transfer must have occurred close to the diapir walls and crest to cement these fractures.

8. The Palaeocene clastic rocks were deformed when the sediment was still un lithified, with slump folds being most common in the shales. Fold asymmetry is generally consistent with downslope sliding off the crest. Slump folding is best preserved at farther than 500 m from the diapir crest.

9. The Kyle diapir was exposed at the sea-bed during Palaeocene times, and faulting and/or erosion created high-relief topography so that debris flows of halite, anhydrite and chalk material sloughed off the diapir crest, enhancing further diapir growth.

10. Large (up to 10-cm wide) tension veins, filled with calcite, are developed parallel to bedding in the North Pierce, South Pierce, Mungo, Banff and Kyle diapirs suggesting that overpressured fluids may have been present during deformation of the chalk. Overpressure would help to promote tensile fracturing and shear faulting, facilitating upward movement of the diapirs.

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