Palaeogene remobilized sandstones of the Central North Sea – implications for hydrocarbon migration

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Abstract
There are abundant examples of remobilized sandstones in the Central and Northern North Sea. Study of an area around the Chestnut Field reveals two distinct Eocene sandstone formations, the Caran and Nauchlan, which both show evidence of remobilization. Following a review of the developed and undeveloped discoveries in this area, a trend emerged between these Palaeogene plays. Seemingly robust Palaeocene structures with tested reservoirs, on a known hydrocarbon migration route with overlying seal rocks, were found to be dry where they were overlain by Caran injectites. Elsewhere this same geometry results in hydrocarbons being trapped, but only when overlying Caran injectites are absent. It seems that there is a mutually exclusive relationship between Palaeocene dip-closed structures and overlying injectites. We infer that Caran injectites permit migration into the overlying Nauchlan fairway where hydrocarbons migrate up dip and charge Eocene traps, such as the Chestnut Field. These observations are backed by extensive well data, seismic mapping, fairway mapping, and pressure data. This mutually exclusive relationship may be restricted to areas where an overlying Eocene fairway acts as a migration pathway. Elsewhere these remobilized sands are encased in mudrocks, resulting in hydrocarbons being trapped in Palaeocene structures and associated injectites.

Introduction
Sandstone remobilization has been documented in many fields in the Central and Northern North Sea (Newman et al., 1993; Molyneux et al., 2002; Purvis et al., 2002; Hurst et al., 2003, 2005; Huuse et al., 2001, 2003, 2007; Duranti and Hurst, 2004; Reksten et al., 2011). Recently, injectite plays have attracted much attention following a number of discoveries in Palaeogene remobilized sands. The Catcher discovery, for example, demonstrated that remobilized sands in the Central North Sea, particularly those in the margins of the basin, represent prolific reservoirs which may have been previously overlooked (Encore, 2010). The numerous documented cases of remobilized sands often have excellent reservoir properties, with porosities exceeding 32% and superb permeabilities (Duranti and Hurst, 2004; Huuse et al., 2003; Hurst and Cartwright, 2007). Whilst in some areas these injectite complexes can be highly productive, elsewhere they may have a detrimental effect on the underlying prospectivity.

Remobilized sandstones occur throughout the Viking Graben and Central Graben of the North Sea, primarily within Palaeogene units. The map in Figure 1 shows North Sea hydrocarbon accumulations known to have remobilized sandstone reservoirs or injected sands located above the main reservoir. These include a recent discovery (Catcher), fields under development (Kraken, Mariner), and producing fields (Balder, Alba, and Volund). Therefore, understanding sand remobilization is of significant commercial interest.

Plays and stratigraphy in the Chestnut area
The Chestnut Field is located in block 22/2a of the UK Central North Sea (CNS), approximately 10 km south-east of the Lower Cretaceous Britannia gas condensate field (Figure 2). The Alba Field in block 16/26 opened up the middle Eocene as a play in this region, with the Chestnut Field being the only major discovery since then (Jones et al., 2003). The reservoir within the Chestnut Field is complex, consisting of partially remobilized Nauchlan sandstone.

There are also a number of developed and undeveloped Palaeocene discoveries in the area. These discoveries demonstrate the potential prospectivity of the Forties reservoir in this region.

The area has several proven plays including the Eocene turbidite sandstones of the Chestnut Field (Nauchlan sand) and the Palaeocene Forties interval (Figure 2). Palaeogene reservoirs in the area consist of basinal sandstones, deposited during a period of thermal uplift and subsequent collapse of the Greenland–Faroes–Shetland region (Liu and

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Palaeocene plays are typically deep sea, relatively unconfined, amalgamated turbidite deposits.

Deposition of the Eocene reservoirs followed the basal Eocene transgression which opened the basin to entirely deep marine conditions. During the early Eocene, marine mudstones dominated the stratigraphy and sand bodies became more confined than those deposited during the Palaeocene (Den Hartog Jager et al., 1993). The Nauchlan and Tay systems of the Central North Sea are examples of such confined channel systems.

The Chestnut reservoir is considered to be the distal fan of the Nauchlan fairway, with Alba being the feeder channel up-dip. Huuse et al. (2005) hypothesized that the Chestnut reservoir is a seabed extrudite, formed during Caran remobilization. However, recent geochemical studies undertaken by Centrica (2007, unpublished) have suggested that the Caran and the Nauchlan sandstones are distinct, and therefore the Nauchlan reservoir is more likely to have been deposited as a turbidite and remobilized subsequently.

Hydrocarbons in these Palaeocene and Eocene sands are thought to have migrated laterally over long distances from the mature Upper Jurassic Kimmeridge Clay Formation, a prolific source rock in the Central and Northern North Sea. Migration into these Eocene fairways is relatively poorly understood and has previously been considered to have occurred through a network of strike-slip faults formed...
Figure 3 (a) Caran injectites interpreted on sections through processed 3D seismic data volumes (b) 3D geobody extracted from an inverted shear impedance volume.

Figure 4 (a) Poisson’s ratio geobody extracted over the Chestnut Field. Wells 22/2a-16y and 22/2a-11x are the existing producers and well 22/2a-12 is the existing water injector. Yellow plane shows location of section in (b). (b) Section through shear impedance volume containing trajectories of wells 22/2a-11x and 22/2a-16y. The section shows highly dipping sands associated with remobilization.
during the Miocene (Jones et al., 2003). Hurst et al. (2003) suggested that the underlying Caran injectites may act as conduits, allowing the Nauchlan fairway to be charged. This theory may lead to prospective Eocene targets, but also suggests limited Palaeocene prospectivity in the area.

**Remobilized sand expression**

Caran injectites appear in section as cross-cutting, high amplitude reflectors with V-shaped, Y-shaped, or even W-shaped geometries. Their dips are consistent with the dips of polygonal faults in the area. In the Chestnut area, these injectites appear to terminate close to the middle Eocene unconformity and their origin appears to be proximal to the top Balder horizon which is commonly disrupted. Geobodies extracted from inverted seismic data show the conical nature of these structures. The structures are commonly 600–1000 m wide with a vertical extent of some 160 m (Figure 3). It is not uncommon, particularly beneath the Chestnut Field, to find structures formed by a complex of injectites with W-shaped or even X-shaped geometries resulting from the intersections of sand intrusions.

The Nauchlan Sandstone of the Chestnut Field has different remobilization characteristics from those of the Caran. The Nauchlan Sandstone has a rugose top surface, localized high-angle dips, and complex geometries between sand bodies (Figure 4). The area of the field around wells 22/2a-11x and 11y is considered to have been remobilized because it dips at a similar angle to the polygonal faults cutting the Eocene mudrocks. The geometry seen in Figure 4b is wing-like, as observed in the Alba Field (MacLeod et al., 1999; Huuse et al., 2003).

There are a number of features in the Nauchlan core from Well 22/2a-7z which may indicate post-depositional remobilization, such as discordant mudrocks, high fracture intensity, and rip-up clasts. Similar features have been noted in core from the Alba Field (Hillier and Cosgrove, 2002; Duranti and Hurst, 2004).

**Palaeogene depositional trends**

A number of potentially prolific fairways extended over the study area (Figures 2 and 6). These fairways were mapped using several seismic attributes in conjunction with well log correlations. The Forties fairway (Figure 6) includes the upper and lower Forties systems, which both appear to enter the study area. There are two principal flow directions: WNW–ESE and NNW–SSE. There are significant amounts of reservoir quality sand over the area in turbidites derived from the WNW. Wells in the area have encountered several hundred feet of gross reservoir thickness. The flows from the NNW appear to terminate at the northernmost edge of Block 22/2, with significant volumes of sand being deposited in blocks to the north.

Caran injectites have been mapped on both migrated seismic data and inverted data sets. Their appearance does not correspond to the kind of depositional trend that would be expected in a channelized, deep-water, turbidite. On the contrary, in certain areas, such as the area beneath the Chestnut Field, clusters of injectites form large complexes. There is little Caran sandstone present to the east of the Chestnut Field within the study area.

The Nauchlan fairway is sourced from the NNW and, in part, deposits appear to be stacked compensationally with...
respect to the Forties sandstone, particularly around the Alba Field. Faulting induced by differential compaction probably influenced the fairway distribution, as described by Lonergan and Cartwright (1999). The main Nauchlan fairway terminates at the Chestnut Field, with only very thin, fine-grained sandstones extending further to the SSE.

**Interplay between prospectivity in depositional trends and sand injectites**

Following a review of the developed and undeveloped discoveries in the area, an apparent trend was revealed. Where seemingly robust four-way dip-closed structures are found in the Palaeocene in conjunction with overlying Caran injectites, the Palaeocene structures are dry, despite the presence of abundant reservoir quality sandstones in the Forties Sandstone Member. Elsewhere within the area, four-way dip-closed structures which are not associated with overlying injectites appear to be hydrocarbon-bearing. Hydrocarbon shows are commonly observed within the Forties Sandstone Member in the area, including wells drilled on dry structures, indicating an extremely active hydrocarbon migration system. Regional data also suggest that this fairway is on an active hydrocarbon migration route (Kubala et al., 2003). It therefore seems likely that seal integrity is the principal reason why these dip-closed structures are dry.

Figure 7 shows the mapped structures highlighted with coloured markers. Those which encountered hydrocarbons in the Palaeocene are shown by a green marker and no Caran injectites have been observed above or proximal to them. Those Palaeocene closures that were found to be dry are highlighted by a red marker and all have Caran injectites above the structure. Thus, in this area there is a mutually exclusive relationship between the accumulation of Palaeocene hydrocarbons and the occurrence of Caran injectites.

It is considered that Caran injectites have permitted the migration of hydrocarbons through the otherwise impermeable early Eocene shales where the injectites have intersected the Nauchlan Sandstone fairway. Oil has subsequently migrated up the Nauchlan fairway before becoming trapped in the Chestnut and Alba accumulations.

This migration of hydrocarbons into the Nauchlan fairway limits prospectivity in the Palaeocene sands, and suggests that the Caran intrusions have breached the seal formed by the underlying strata. It might, therefore, be possible that these Caran injectites originate from beneath the Balder and have breached the seals of valid structures in the Palaeocene sandstones of the Sele Formation. There are a number of lines of evidence that appear to support this hypothesis, including disruptions in the top Balder seismic reflector, mapped injectites with apexes which appear to originate at or beneath Balder Tuff, and conduits observed beneath the Caran injectites that appear to originate from beneath the Balder reflector. Additionally, RFT pressure data over the area show that the Nauchlan, Caran, and Forties sandstone
members all appear to plot on a hydrostatic pressure gradient, suggesting that they are in pressure communication. Alternatively, if the sands do not originate from a Palaeocene source, the proximity of the injectites to the seal rocks may allow migration to occur over short distances through polygonal faults which would otherwise heal without the overlying injectites (Figure 8).

Example 1 – Palaeocene failed traps
There are a number of examples of failed Palaeocene traps in this area where seal integrity appears to have been the principal reason for failure. One such example is defined by a robust four-way dip-closed structure observed at the Sele Formation level. The structure has a number of wells proximal to, and located within, the limits of the structure (Figure 9).

Well A encountered a thick succession of Forties sandstone within the main fairway overlain by Sele Formation shale (the regional seal). Despite a valid reservoir, migration route, seal, and robust four-way dip closure, no hydrocarbons were encountered in this well. Wells B and Bz encountered over 300ft of gross reservoir that consisted of fine-grained sandstone of reservoir quality with minor shows in the uppermost Palaeocene sands and occasional silt and shale beds. These wells are located very close to the limits of this four-way dip-closed structure. Well C encountered fine-grained to medium-grained water-bearing Palaeocene sands of reservoir quality. It seems that, despite abundant upper Palaeocene sands being present, there was little more than some minor shows within the limits of the closure. Interestingly, as well as proving Forties sandstones, Well C encountered Caran Sandstone with an apparent thickness of 30 m. This extremely clean, blocky sandstone was clearly imaged on seismic data (Figure 9). The Caran Sandstone at this location appears to intercept the top Balder surface within the limits of the defined four-way dip closure. We suggest that, given the observed shows in this area, it is likely that the failure of this structure is due to seal integrity. This is one of several seemingly robust structures with overlying injectites which were discovered to be water-bearing. Seismic...
inversion suggests that these structures are water-bearing and are not under-filled.

Example 2 – Palaeocene success
There are several developed and undeveloped discoveries in Palaeocene strata within the area, none of which have Caran injectites located above them. One such discovery is shown in Figure 10. Well D drilled on this structure revealed a clean Forties sandstone with bright fluorescence through the Palaeocene section and an oil–water contact picked from wireline logs that is coincident with the structure’s spill point. The pressure–depth profile interpolated from RFT measurements in the well is consistent with the above observations.

Example 3 – Chestnut Field Eocene migration
The seismic data over the Chestnut Field reveal a number of examples where the Caran appears to be in connection with Palaeocene strata. Additionally, a number of Caran injectites appear to cross-cut the Nauchlan fairway. These observations are consistent with those made by Huuse et al., 2005 (Figure 11). It therefore seems likely that the Caran injectites have provided the migration pathway for hydrocarbons to enter the Nauchlan fairway at its most distal location down-dip, charging the Chestnut reservoir before further migration up-dip to the Alba Field. Without the presence of the underlying injectites, there would be no possible hydrocarbon migration pathway into the formation because a thick succession of impermeable shales underlies the Chestnut Field.

Relationship between trapping, injectites, and hydrocarbon migration
From detailed mapping of the Palaeocene and Eocene strata within the study area, it appears that where sand intrusions occur above Palaeocene dip closures, wells are dry at the Palaeocene level. Similar tested structures in Palaeocene
strata where such intrusions are absent do contain hydrocarbon accumulations.

Combining observations made within this study area with a regional overview of injectites in the North Sea allows for a number of conceptual trapping geometries and migration routes into Eocene strata to be explored. Figure 12 shows several such geometries. Geometries A and C show how Caran injectites act as conduits, limiting Palaeocene prospectivity but providing a migration route into early Eocene (A) or middle Eocene (C) fairways. Such examples have been demonstrated in this paper and provide a migration route for charging the Chestnut Field. Where no Caran injectites occur above Palaeocene structural closures (B), there is no migration route into the overlying Eocene strata. This robust trapping style is found in this area (Figure 10) and numerous fields in the Central North Sea (Ahmadi et
al., 2003; Zanella and Coward, 2003). Where no fairway overlies the Caran (D), there may be situations where both Palaeocene depositional sands and overlying injectites are hydrocarbon-bearing. In this situation the injectites are encased by impermeable Eocene shales which do not permit hydrocarbon migration into the overlying strata. Examples of fields which display this geometry have been described in Gryphon (Newman et al., 1993). If the overlying Eocene fairways are stratigraphically trapped (E), it may be possible that there is stacked pay in the Eocene sands, Caran sands, and Palaeocene sands.

Polygonal faulting relationship

Polygonal faulting associated with the compaction of clay-rich sediments is pervasive throughout the study area within the Eocene to Miocene strata (Figure 13). The polygonal faulting is readily apparent on seismic data and is located in tiers that correlate with log character variations in the claystone sequence observed from well data. As Figure 13 demonstrates, no systematic fault trend is identified. The dip angles and horizontal scale observed in both the sand injectite features and the polygonal faulting are similar. This phenomenon has been studied in the adjacent Alba Field (Lonergan and Cartwright, 1999), where it is hypothesized that sand remobilization exploits the incipient polygonal fault systems. This possible exploitation of the polygonal fault network by remobilized sands may explain the unusually large scale of the injectite bodies, particularly in the Caran Formation. The fault network would reduce the threshold pressure that needs to be overcome to initiate the remobilization event. The polygonal fault networks do not commonly extend into the more widespread Palaeocene submarine fans, rather they terminate in the claystone sequence immediately overlying the Balder Formation; however, any minor tectonic faults cutting the top Balder horizon are likely to tap into the polygonal fault network.

Trigger mechanisms

Mechanisms to initiate sand remobilization have been studied elsewhere in detail (e.g. Duranti et al., 2002; Molyneux et al., 2002; Duranti, 2007). Sand remobilization requires a pressure differential with respect to the overlying (or underlying) units. The most commonly suggested mechanisms include:

- Earthquake-induced liquefaction, aided by early gas charge within the source sand.
- Pressure disequilibrium caused by encasement of the source sandstone and constituent pore fluid by impermeable, fine-grained sediment.
- Liquefaction caused by other external events, e.g., slumping, severe weather.

The first mechanism listed has often been cited as the most likely cause for North Sea Palaeogene injectite events.

Implications for hydrocarbon prospectivity

There are several implications when considering Palaeocene structures in known injectite provinces. Any Palaeocene
structures should have adequate interpretation of the overburden to assess for injectites. If injectites are observed, then the interpreter must assess the potential of leakage into overlying strata. If a known fairway is stratigraphically above the injectites, then consideration of the trapping risk must be fully evaluated. If the overburden is mudrock-dominated with little potential for carrier beds, then there may be additional upside in the remobilized sands. For Eocene targets, underlying injectites may provide a migration pathway and are favourable to charge Eocene structures.

Conclusions
We have found a mutually exclusive relationship between hydrocarbon occurrences contained within the Palaeocene and overlying injected Caran sandstones. It seems that, in the study area, the overlying injectites allow migration of hydrocarbons from the Palaeocene into the overlying Nauchlan fairway. There are several examples where seemingly robust Palaeocene structures, with abundant sand on a proven hydrocarbon migration route, appear to be water-bearing. All the failed structures seem to occur in conjunction with overlying Caran injectites. Those structures which contain hydrocarbons within the Palaeocene strata appear not to have this migration route into the overlying Eocene Nauchlan fairway.

This relationship, combined with seismic observations of the injectites and the apparent pressure communication between all three sands, may suggest that the Caran sands were entirely remobilized from a pre-Balder source, allowing seal breach of Palaeocene structures. Alternatively, if Caran sands are remobilized sands that were originally deposited during the early Eocene, migration may occur over short distances through polygonal faults, which might otherwise have healed over time without the overlying injectites. The combination of remobilized sands and an overlying (Nauchlan) fairway limits the trapping potential of Palaeocene structures, but does provide a migration route for hydrocarbons to charge the Chestnut and Alba fields. Elsewhere in the North Sea, there are numerous examples where overlying carrier beds are absent and both injectites and the Palaeocene sands are hydrocarbon-bearing (Purvis et al., 2002; Newman et al., 2003; Briedis et al., 2007). In these cases, remobilized sands are encased in impermeable mudrocks of early Eocene age and may add reserves and/or be targets themselves. These observations have implications for assessing the Palaeocene and Eocene prospectivity in areas where sands have been remobilized.

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