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Sandstone intrusions: detection and significance for exploration and production

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Summary

Early recognition of sandstone intrusions is a key factor in maximising exploration and production success of the Paleogene deepwater sandstone reservoirs of the northern North Sea. Discordant sandstone intrusions are readily detected in cores, image logs and high quality seismic data by cross-cutting relations with the encasing shales. Many examples of "ratty" sands seen in borehole logs and "artefacts" or "channel margins" seen in seismic data have later proven to be sandstone intrusions, with significant implications for exploration and production. The effects of sand remobilisation and injection include increased connectivity between reservoir compartments, thief sands caused by brecciation and injection into the seal, and large-scale modifications of reservoir geometry, in particular top reservoir. Detailed case studies from the North Sea Paleogene and pilot studies including various other deepwater clastic successions indicate that sandstone intrusions could prove to be an important factor in the development of some highly prolific deepwater provinces such as the West African Atlantic margin. Early recognition of sandstone intrusions in such areas is important for optimal development planning. It requires that the appropriate borehole and seismic data are acquired, and that sandstone intrusions are incorporated in the interpreter's mindset.

Introduction

Sandstone intrusions are the products of post-depositional remobilisation and injection of sand. They comprise sandstone dykes and sills, and injection breccias. Outcrop examples of sandstone intrusions have been known for over a century (e.g. Newsom 1903), but were only recently recognised in the subsurface. Over the last decade it has emerged that numerous Paleogene reservoirs of the northern North Sea have been subjected to large-scale remobilisation and injection of sand (Figs 1, 2; Newman *et al.* 1993; Newton & Flanagan 1993; Dixon *et al.* 1995; MacLeod *et al.* 1999; Lonergan *et al.* 2000; Duranti *et al.* 2002a). Effects of such large-scale remobilisation comprise changes in reservoir geometry (Dixon *et al.* 1995; Lonergan *et al.* 2000) and reservoir properties (Duranti *et al.* 2002a), intra-field connectivity (Guargena *et al.* 2002) and brecciation of the top seal (Templeton *et al.* 2002). The sum of these effects may be both positive and negative for hydrocarbon prospectivity, but in any case it is vital to determine the effects in order to optimally explore for and produce reserves hosted in remobilised reservoirs.

The present paper outlines criteria for the recognition of sandstone intrusions in the subsurface and briefly summarises the significance of post-depositional remobilisation and injection of sand for exploration and production of hydrocarbons. The findings presented here are based on experience gathered through the first phase of an industry sponsored research project (www.injectedsands.com). The project involved detailed subsurface case studies from the North Sea Paleogene, supplemented with outcrop studies and brief reviews of subsurface data from deepwater hydrocarbon provinces elsewhere. Our results indicate that sandstone intrusions may be significant for several hydrocarbon plays other than the North Sea Paleogene. These include the Jurassic and Lower Cretaceous of the North Sea, the Jurassic, Cretaceous and Paleogene of the NW European Atlantic Margin, the Cretaceous-Paleogene of central California, and the Cenozoic offshore West Africa (Injected Sands Group unpublished data). The common occurrence of sandstone intrusions in the data sets examined suggests that they may also be common in other deepwater clastic provinces, such as offshore Brazil, the SE Mediterranean, the Gulf of Mexico, etc.

Sandstone intrusions in association with North Sea oil fields have usually been encountered when exploring for deeper targets, or during the appraisal and production phase of accumulations hosted in assumed "conventional" deepwater sandstone bodies. The sand injectites, as they are known, drilled in the North Sea are often highly porous with Darcy-range permeabilities (MacLeod *et al.* 1999; Lonergan *et al.* 2000; Duranti *et al.* 2002a), making them effective both as reservoirs and as thief sands. Recognition and evaluation of sand injectites can thus be vital for the appraisal and production of reservoirs affected by remobilisation and injection.

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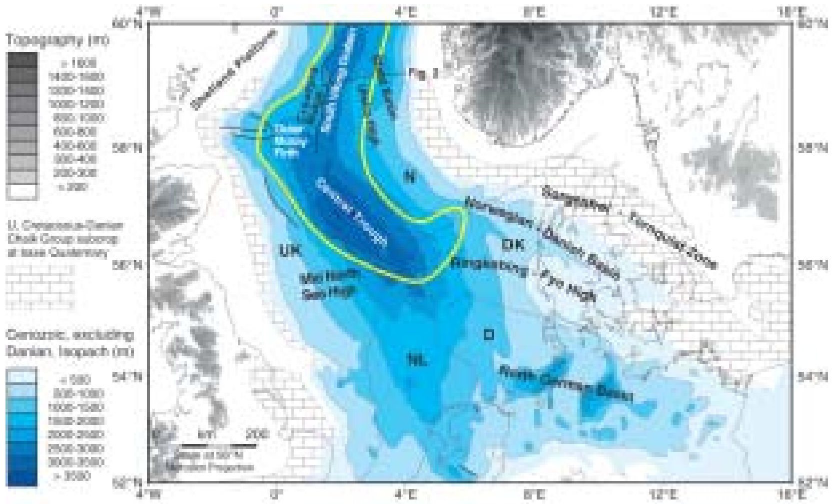

Figure 1 *Depth to the base of the Cenozoic (excl. Danian) and location of major Mesozoic structural elements in the North Sea Basin. Paleogene deepwater sandbodies affected by post-depositional remobilisation and injection mainly occur within the yellow outline.*

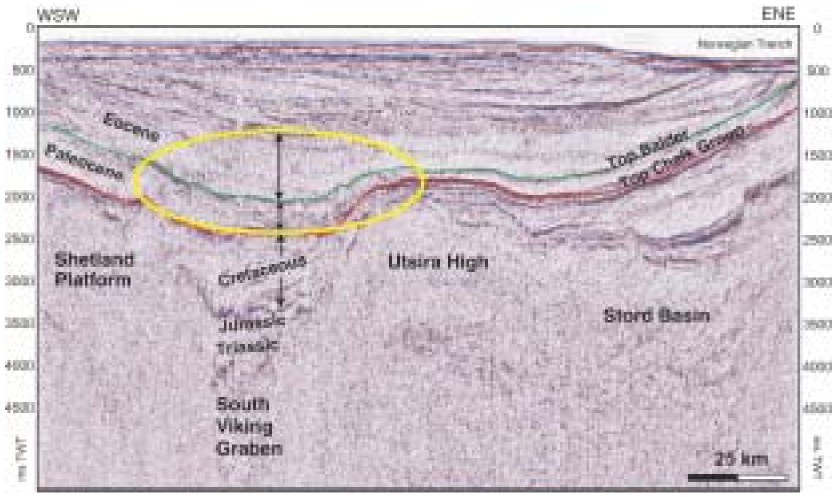

Figure 2 *Regional seismic cross-section showing the location of remobilised and injected fields (within yellow outline) in relation to the main structural and stratigraphic elements of the northern North Sea (~60∞N). Location of seismic line is shown on Figure 1.*

Detection of sandstone intrusions in boreholes

Sandstone intrusions in the subsurface are most readily identified in cores, where they display cross-cutting relations with the encasing shales (Fig. 3; Dixon *et al*. 1995; Lonergan *et al.* 2000; Duranti *et al.* 2002a). Dykes cross-cut stratigraphy and, when thin, may display ptygmatic folding, indicative of intrusion prior to shale compaction (Hillier & Cosgrove 2002). The differentiation between sandstone sills and depositional sandstone units is comparatively equivocal, but sills may be identified by the abrupt, sometimes irregular, non-depositional contacts with under- and over-lying shales, which often display subtle truncations (Fig. 3; Dixon *et al.* 1995; Duranti *et al.* 2002a). Scours are also common at the base of gravity flow deposits, but truncation of the overlying shales is atypical of depositional processes and indicative of intrusions. Injection breccias often resemble debris flow deposits (Fig. 3), but relations with host shales and the fabric of the shale clasts (tapered edges and clast connections)

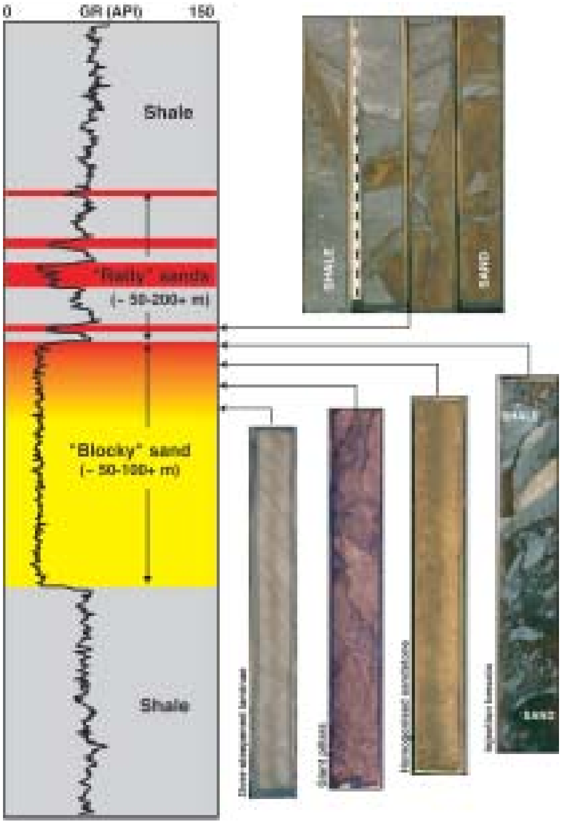

Figure 3 *Conceptual diagram of a borehole section through a remobilised lower Paleogene turbidite reservoir from the northern North Sea: gamma-ray (GR) log and lithology with core photographs showing a facies association of remobilisation and injection features (see Duranti et al. 2002a for discussion). Each core section is approximately 3 ft (~0.9 m long). Shales are grey, yellow indicates non-remobilised sand, and red represents remobilised and injected sandstones. Core photographs are from Duranti et al. (2002a) and Purvis et al. (2002). The conventional interpretation of the thin ("ratty") sandstones indicated by the GR log above the main reservoir would be as depositional sand units, but careful core analysis allows distinction between depositional and injected sandstones.*

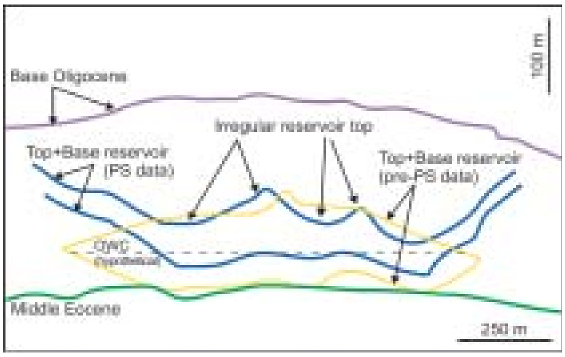

Figure 4 *Schematic cross-section of the main reservoir unit of the Alba Field showing the interpreted outline of the reservoir before and after acquisition of OBC data (cf. MacLeod et al. 1999; figure modified from Jones et al. 2003). Note irregular crest and cross-cutting wing-like anomalies at the edges of the Alba reservoir seen on the PS data. The irregular reservoir top and the "wings" have been calibrated by numerous pilot and production boreholes showing the wing-like anomalies to represent several metres thick sandstones of excellent reservoir quality (MacLeod et al. 1999).*

may be used to identify them as intrusive features. Like depositional facies, the interpretation of sandstone intrusions is facilitated by facies associations (Fig. 3; Duranti *et al.* 2002a).

Core records from sections above thick turbidite reservoirs indicate that the thin-bedded ("ratty") sandstones often identified using gamma-ray logs may, in fact, represent sandstone intrusions rather than thin turbidites, as they are commonly interpreted (Fig. 3; cf. Newman *et al.* 1993; Dixon *et al.* 1995; Duranti *et al.* 2002a). When core records are absent, it is sometimes possible to identify the discordant nature of the sandstone units using dipmeter or image logs.

Fields associated with sandstone intrusions in core are often also associated with cross-cutting events on seismic data (Fig. 4), especially when the main reservoir sand was deposited in a distal setting isolated from major basinal aquifers (Dixon *et al.* 1995; Lonergan *et al.* 2000; Duranti *et al.* 2002a; Huuse *et al.* in press).

Detection of injected sandbodies in seismic data

Seismic-scale features related to sandstone intrusion comprise two major classes:

1. Cross-cutting wing-like reflections that emanate from the edges of isolated steep-sided sandbodies, often terminating at unconformities in the overburden (Figs 4-7)
2. V-shaped (in 2D) or conical (in 3D) discordant amplitude anomalies not visibly in connection with underlying sandbodies (Figs 4, 8)

1. Wing-like reflections have been documented from a number of isolated sandstone accumulations in the northern North Sea (Figs 4-7; Dixon *et al.* 1995; Lonergan & Cartwright 1999; MacLeod *et al.* 1999; Cole *et al.* 2000; Molyneux 2001; Huuse *et al.* in press). Their significance was not fully appreciated until OBC seismic data of the Alba Field allowed pilot and production boreholes to target the "wings", calibrating them to tens of metres thick sandstones of excellent reservoir quality (Fig. 4; MacLeod *et al.* 1999).

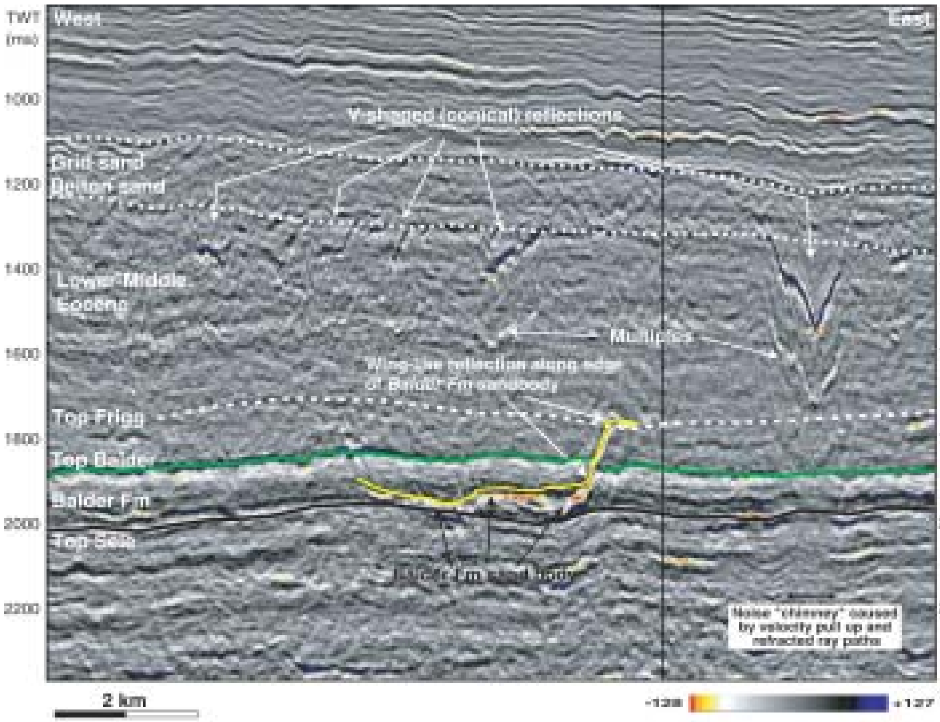

Figure 5 *Conventional P-wave seismic section showing the two major classes of seismic-scale injection features: Wing-like amplitude anomalies (low-angle sandstone dykes) emanating from the sides of steep-sided sandbodies and conical amplitude anomalies (conical sandstone intrusions) detached from underlying sandbodies. Figure modified from Huuse et al. (in press). Location of seismic line is indicated on Fig. 7*

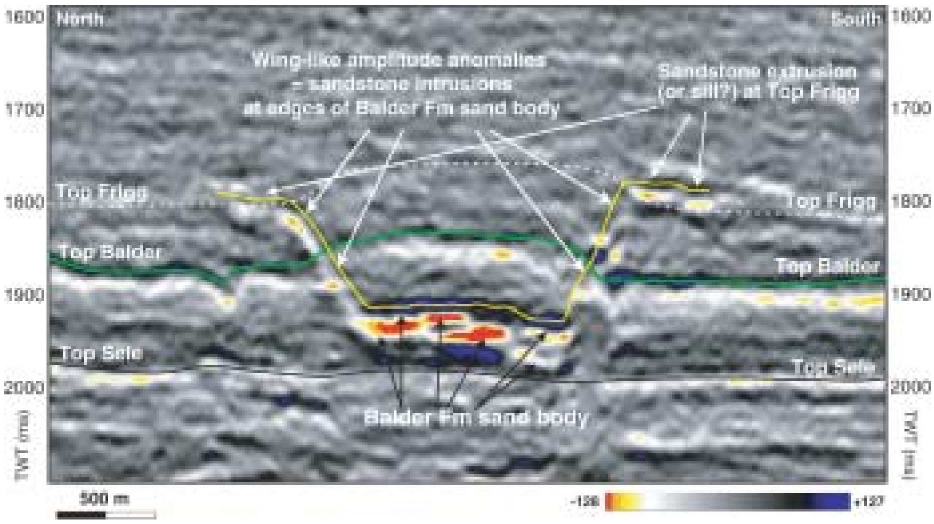

Figure 6 *Conventional P-wave seismic section across a steep-sided sandbody in the Balder Formation with cross-cutting wing-like reflections emanating from its sides. The cross-cutting reflections are interpreted as large-scale injected sandstones (low-angle dykes). Cores from the crestal part of the sandbody display numerous injection features, confirming that the main sandbody has been affected by remobilisation and injection. Figure modified from Huuse et al. (in press). Location of seismic line is indicated on Fig. 7.*

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Acquisition of OBC seismic was justified by poor acoustic impedance contrast between the oil-filled reservoir and the encasing shales, which did not allow a confident top reservoir pick, whilst the elastic impedance contrast was much greater, causing a well-defined reflection at top reservoir on converted-wave (PS) seismic data (Fig. 4, MacLeod *et al.* 1999).

The wing-like reflections occur along the flanks of steep-sided sandbodies, which are thought to have formed either due to sand diapirism (Dixon *et al.* 1995) or differential compaction between sand and encasing shales (Hillier & Cosgrove 2002). The available well control indicates that the wings represent low-angle (~30-45°) sandstone dykes, up to a few tens of metres thick and cross-cutting up to 200-250 m of compacted strata. Dykes may continue for some kilometres along strike and they may turn into sills and/or palaeo-seafloor extrusions at their tips (Figs 5-7).

The volume of sandstone represented by the wing-like anomaly seen in Figures 5-7 is difficult to estimate, as no well calibration of the feature exists. However, a wing-like reflection emanating from a Balder Formation sand body a few km to the southwest of the structure has been calibrated in a borehole as a 30-40 m thick sandstone (Huuse *et al.* in press). This "wing" had similar stratigraphic and geometrical characteristics to the one shown here, and the calibration point was a few hundred metres from the source sandbody. The volume of the "wing" shown in Figures 5-7 may be estimated, knowing its areal extent (Fig. 7A) and assuming a uniform vertical thickness of 20 m throughout the extent of the wing-like amplitude anomaly. The resulting volume is of the order of $1x10^8$ m^3. Assuming a sandstone porosity of 30%, the pore volume would be of the order of $3x10^7$ m^3 or some $200x10^6$ barrels. When wing-like intrusions are directly associated with proven hydrocarbon accumulations they thus represent significant potential upsides to proven reserves. However, sandstone intrusions are highly variable in terms of thickness, net/gross ratio and cementation, and there are only a few examples of deliberate targeting of wing-like intrusions by production wells. Hence, if no well calibration is available the quantification of pore volume and pore fluid is generally perceived as high risk (Hurst *et al.* 2002).

2. Conical amplitude anomalies are ubiquitous in the Lower-Middle Eocene throughout the Northern North Sea, from the Outer Moray Firth through the South Viking Graben to the North Viking Graben. However, they have only recently been documented (Figs 4, 8; Molyneux 2001; Gras & Cartwright 2002; Molyneux *et al.* 2002; Løseth *et al.* 2003; Huuse *et al.* in press). Similar anomalies have been detected in the upper Paleogene of the Faeroe-Shetland Basin and in the Neogene of the Taranaki Basin, New Zealand (Huuse *et al.* 2001; Hurst *et al.* 2003). In the past, well paths were probably designed to avoid the anomalies as their bright reflection response and unknown origin represented a potential drilling hazard. Nonetheless, a number of well penetrations do exist, all of them yielding tens of metres thick sandstones of varying degrees of cementation (Molyneux 2001; Gras & Cartwright 2002; Molyneux *et al.* 2002; Huuse *et al.* 2003; Løseth *et al.* 2003). The anomalies are thus interpreted as conical sandstone intrusions, possibly fed by blow-out pipes originating at the top of underlying aquifers (cf. Løseth *et al.* 2001; Huuse *et al.* 2003).

The dimensions of the intrusions are of the order of 100-300 m in height, and 500-1500 m in diameter, with flank dips of the order of 15-45°. Their geometry is similar to the geometry of polygonal fault systems, which are known to pervasively deform the host formation of the intrusions. This correspondence has led to the inference that the conical intrusions exploit polygonal faults (Gras & Cartwright 2002; Molyneux *et al.* 2002). However, it is clear that polygonal fault cells themselves are not conical (with distinct apexes) and that parts of the intrusions do not coincide with faults (Huuse *et al.* 2003), suggesting that the intrusions may exploit polygonal faults, but will achieve their conical geometry irrespective of the fault pattern in the host formation.

The volumes of a conical sandstone intrusion may be estimated from its areal extent (~0.5-1.5 km width) and its apparent thickness in vertical boreholes (~20-50 m). The range of volumes bracketed by these values is $4x10^6 – 9x10^7$ m^3, with typical volumes averaging 1-$3x10^7$ m^3. Assuming an average sandstone porosity of 20%, the pore volume of a typical intrusion (bulk volume ~ $2x10^7$ m^3) may be of the order of 3-$4x10^6$ m^3 or about $20x10^6$ barrels. Note that these are very coarse estimates subject to large variations depending on the actual thickness, net/gross ratio and cementation of the sandstones. These factors are difficult to quantify using seismic data alone.

Seismic imaging of sandstone intrusions

The dimensions of injected sandbodies encountered both in outcrop and in the subsurface range from millimetre to kilometre scale (Newsom 1903; Dixon *et al.* 1995; MacLeod *et al.* 1999; Jolly & Lonergan 2002; Gras & Cartwright 2002; Molyneux *et al.* 2002; Huuse *et al.* 2003). Outcrop and borehole observations provide a much higher level of detail but sample a smaller rock volume than seismic data. Hence there is often an order of magnitude difference between injected sandbodies seen in borehole or outcrop and those detected using seismic data. From boreholes and outcrops it appears that cm- to m-thick intrusions are most common, although intrusion complexes may be several tens of metres thick. Only intrusions or intrusion complexes thicker than a metre or so are detected by even high quality 3D seismic data. The thickness of even large-scale injected sandbodies is usually close to or less than the seismic resolution (tuning thickness, $\lambda/4$ ~ 20 m) making it very difficult to quantify the volumes of intrusions and of hydrocarbons present within them.

The seismic expression of large-scale injected sandbodies is determined by the interplay between sandbody geometry, acoustic properties of the sand and the encasing shales, and the quality of the seismic processing. Recently, it has been demonstrated that imaging and processing difficulties may hamper the detection and proper interpretation of large-scale injected sandbodies, leading to mis-representation of their geometry and under-estimation of their occurrence and volumes (MacLeod *et al.* 1999; Luchford 2002). Imaging difficulties may be related to poor contrasts in acoustic impedance between sands and shales (MacLeod *et al.* 1999; Hoare 2001), to seismic anisotropy (Mikhailov *et al.* 2001), or may be due to steeply dipping sandbodies not being properly imaged by conventional post stack migration of seismic data (Luchford 2002). In the case of poor acoustic impedance contrast, either long offset stacks or OBC converted wave data may improve imaging (MacLeod *et al.* 1999; Hoare 2001; Gras & Cartwright 2002), while steep dips may be more accurately imaged by applying (anisotropic) pre-stack migration (Mikhailov *et al.* 2001; Luchford 2002).

Polygonal faults, forced folds and seismic-scale sandstone intrusions

The localisation of the wing-like sandstone intrusions along the edges of the Alba Field have been associated with two main controls: 1) polygonal faults in the surrounding claystones (Lonergan & Cartwright 1999), and 2) forced folds of the overburden due to differential compaction across the Alba sandbody and encasing mudstones during early burial (Cosgrove & Hillier 2000). However, the relative significance of polygonal faulting and forced folding on sand remobilisation and injection is difficult to assess for the Alba Field because several tiers of polygonal faults interact at the reservoir level.

In contrast, the wing-like intrusion shown in Figures 5-7 is only affected by one tier of polygonal faults and it can be seen that only about 25% of the intrusion coincides with polygonal faults whilst there is a 100% correspondence between the extent of the intrusion and the edge of the source sandbody (Fig. 7; Injected Sands Group unpublished data).

The main control on the localisation of wing-like intrusions thus appears to be the forced folds developed during early burial and differential compaction of a sandbody encased in muds (cf. Cosgrove & Hillier 2000), whilst polygonal faults intersecting the reservoir may have a more localised influence on intrusion geometry.

Conical sandstone intrusions and polygonal fault systems display geometrical similarities. They sometimes coincide in seismic displays, and both occur within the Lower-Middle Eocene of the northern North Sea. These observations have led to the inference that the conical intrusion geometry was achieved by sand injection along polygonal faults (Lonergan *et al.* 2000; Gras & Cartwright 2002; Molyneux *et al.* 2002). However, although the foregoing observations are correct, it should be noted that polygonal fault cells are very rarely cone-shaped. They usually have at least one segment dipping away from the centre of the cell, and individual fault segments usually do not meet in distinct apexes (Cartwright & Lonergan 1996; Lonergan *et al.* 1998). It is thus difficult to envisage how the conical intrusion geometry could be controlled by polygonal faults. Moreover, detailed mapping of well-defined conical intrusions show that only parts of the intrusions coincide with polygonal faults and there are furthermore cases where intrusions cross-cut polygonal faults and vice versa (Huuse *et al.* 2001, in press).

Hence, it appears that conical sandstone intrusions achieve their shape whether polygonal faults are present or not, and only exploit polygonal faults when these are favourably oriented. Polygonal faults may, however, have acted as conduits for upward transport of sand to the apexes of the conical intrusions, possibly focused along the intersection between individual fault segments (cf. Lonergan *et al.* 1998; Gay 2002). The geometrical similarities of conical sandstone intrusions and polygonal faults and their ubiquitous development within the very fine grained and smectite-rich Lower-Middle Eocene section of the northern North Sea suggests that their geometries are controlled by the rheological properties of the host mudstones.

Mechanisms of large-scale sand remobilisation

The exact mechanisms triggering and driving large-scale remobilisation and injection of deepwater sandbodies remain poorly understood (cf. Jolly & Lonergan 2002). The main requirement for large-scale sand remobilisation appears to be the development of overpressure in an unconsolidated sandbody encased in very fine-grained mudstones. Early sealing of sand units by surrounding fine-grained sediments may lead to overpressure development due to disequilibrium compaction (Osborne & Swarbrick 1997). Another mechanism for generating overpressure in shallow reservoirs is lateral transfer of fluids from deeper overpressured parts of a basin via inclined aquifers (Yardley & Swarbrick 2000). The processes of disequilibrium, compaction and lateral transfer are amplified in the event of hydrocarbon (gas) charge, a factor often inferred to drive sand injection (e.g. Lonergan *et al.* 2000; Molyneux 2001; Duranti *et al.* 2002b). If the top seal of an overpressured reservoir fails, sand may become remobilised by fluidisation as excess pore fluids are expelled through breaches in the sealing layer into the water column or into a shallower aquifer. While it is generally accepted that sand injection is driven by the pressure gradient established when the seal of an overpressured sandbody is breached, the mechanism by which the seal is breached has been subject to considerable speculation.

As discussed above, the seal may be breached due to stresses caused by forced folding or by polygonal faults. Another viable mechanism for the initiation of top seal failure is earthquake activity (Jolly & Lonergan 2002; Molyneux *et al.* 2002). Tectonic shaking may cause seal failure by weakening the seal itself and by triggering dynamic liquefaction of the reservoir sand leading to abruptly increased pore pressures. The main evidence for earthquake-triggered top seal failure is the association of many recent sandstone intrusions

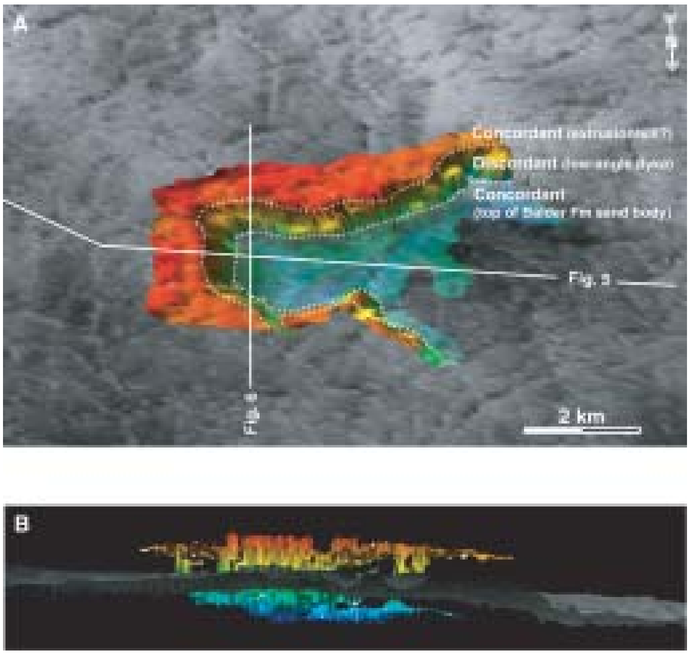

Figure 7 *Perspective view of the polygonally faulted Top Balder reflection (grey, semi-transparent) cross-cut by the yellow reflection indicated on Figures 5 and 6 (horizon coloured by spectrum from about 1700 ms to 1950 ms TWT). Blue colours coincide with the top of the conformable Balder Formation sandstone; green-yellow correspond to the cross-cutting part of the wing-like reflection, whilst orange-red colours correspond to anomalous amplitudes conformable with the top Frigg reflection. (A) Perspective view looking south. From Huuse et al. (in press). (B) View looking south along the Top Balder horizon.*

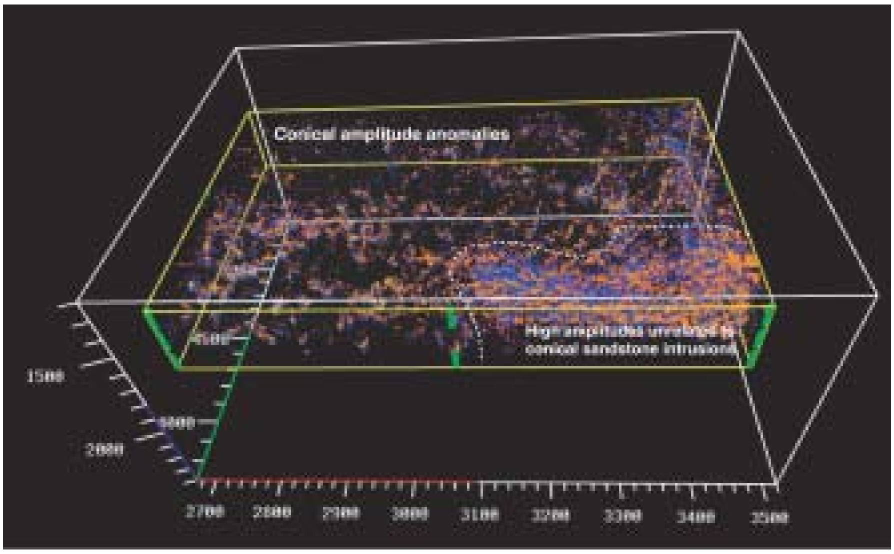

Figure 8 *Volume visualisation showing the pervasive occurrence of conical amplitude anomalies in the Lower-Middle Eocene of the South Viking Graben. All but the highest positive and negative amplitudes are rendered transparent. The volume is about 18 km wide, 12 km deep and 400 ms TWT high.*

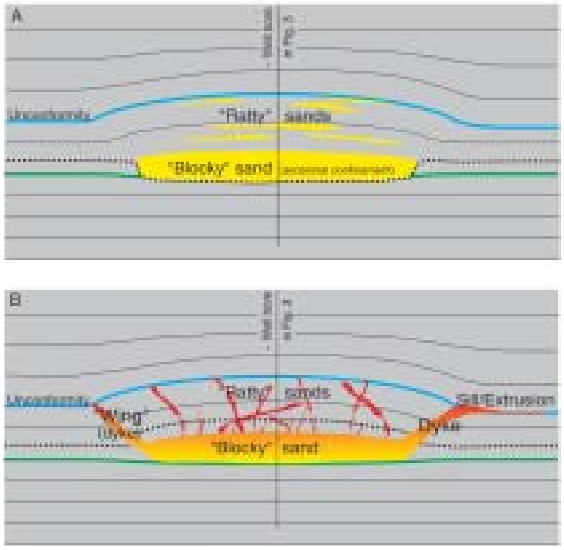

Figure 9 *Models of sandstone distribution and geometries vary depending on data quality and interpretation mind-set. Discordant reflections on seismic, and "ratty" sands indicated by GR logs, may be interpreted as (A) massive sand confined to erosional scour overlain by thin-bedded turbidites, or (B) massive sand with no apparent confinement and differential compaction of encasing shales; the "ratty" sands seen on gamma-ray logs may be interpreted as sand injectites in the overburden shales, and wing-like seismic reflections at the edges of the sand may be interpreted as low-angle sand dykes and sills/extrusions (red = remobilised/injected; yellow = in situ). The two models require different production strategies as depicted in Fig. 10.*

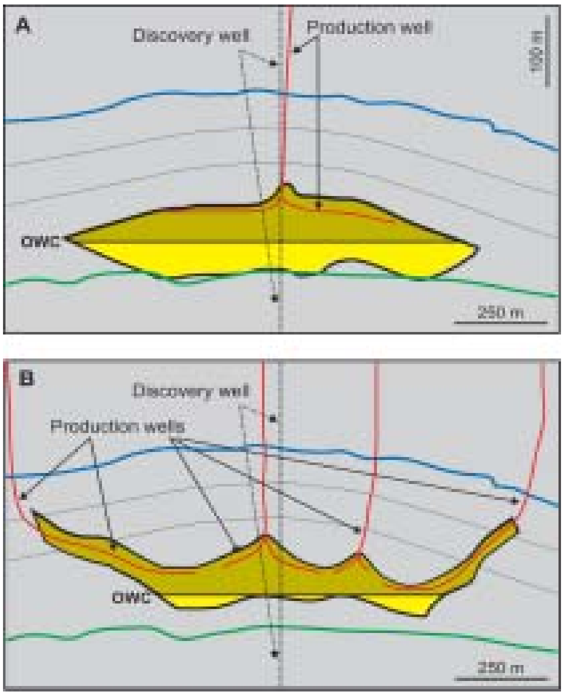

Figure 10 *Planning of production wells is dependent on the geological model, which, in turn, is dependent on the quality of the available data and the interpreters mindset. The two scenarios are based on the models of the Alba Field pre- and post-OBC interpretation of reservoir geometry (Fig. 4). Non-remobilised reservoirs (A) may only require crestal production wells whereas extensively remobilised reservoirs (B) may require wells to be drilled on local crests and along marginal intrusions to drain the reservoir optimally.*

with seismicity in active fault zones (e.g. Obermeier 1989). It has been argued that the Paleogene North Sea Basin was a tectonically quiescent environment and that earthquakes therefore would be an unlikely trigger of sand remobilisation (Jolly & Lonergan 2002). However, the remobilisation of deepwater sands in the North Sea Basin took place over an extended period of time (Upper Paleocene-Eocene ~ 25 Myr), when tectonic activity in relation to North Atlantic break up and Alpine collision caused basin inversion throughout NW Europe. It is thus not inconceivable that seal rupture could have been triggered by earthquake activity.

Significance of sandstone intrusions for exploration and production

The processes of sand remobilisation and injection lead to considerable reconfiguration of the source sandbodies. This, in turn, can have a number of important consequences for hydrocarbon exploration and production. The main points of concern are:

1. changes in reservoir geometry (including top reservoir structure)
2. changes in reservoir connectivity
3. breaches of the top seal (injection breccias; thief sands)

1. Large-scale sand intrusion and associated withdrawal of sand from the source sandbody modify the original depositional geometry of the sandbody and thus may hamper the reconstruction of its depositional architecture (Fig. 4; Dixon *et al.* 1995; Lonergan & Cartwright 1999; Duranti *et al.* 2002a; Jones *et al.* 2003). Picking of the reservoir top is usually complicated in these cases, since top reservoir does not correspond to a stratigraphic surface but frequently jumps from "high" injected units to the "depressed" top of the source body (Figs 4, 9, 10). The irregular reservoir top, which is often difficult to constrain using seismic and borehole data, causes problems for the optimal placement of production wells (Fig. 10).

2. Large-scale injected sandbodies seen in the Cenozoic of the North Sea Basin may cross-cut tens to a few hundred metres of present-day (i.e. compacted) strata, and may extend for several hundred metres laterally away from the parent sandbody. Because of their often high permeabilities, injected sandbodies provide efficient connections vertically between sandbodies located at different stratigraphic levels, and laterally between adjacent sand accumulations (Guargena *et al*. 2002; Purvis *et al*. 2002). The presence of such high permeability connections across thick packages of impermeable strata clearly has a strong influence on compaction and long-term fluid flow in sedimentary basins (Jenkins 1930; Hurst *et al*. 2003).

3. In cases where injected sandbodies are relatively thick and laterally continuous they may constitute exploration targets in their own right, or provide additional reserves to existing discoveries. In extreme cases, however, most of the oil column may reside within injected sandbodies or injection breccias (Templeton *et al*. 2002), potentially causing severe problems to hydrocarbon production. If the injected sandbodies are discontinuous or very irregular they may act as thief sands, dispersing any hydrocarbons into sub-economic accumulations. Sandstone intrusions may act as thief zones for drilling fluids resulting in unexpected losses during exploration and production drilling.

Hence, sand injectites detected by seismic data may be viewed as both prospective and as a risk, depending on how their geometry and reservoir characteristics are interpreted from the available seismic and borehole data (cf. Fig. 9). The recognition and volumetric interpretation of injection features can thus be essential for accurate reserve assessment and for optimal development planning (Figs 4, 10; MacLeod *et al*. 1999).

Although it has been shown that cross-cutting reflections at the edges of thick isolated sandbodies may represent tens of metres thick sandbodies of excellent reservoir quality, such features do not appear to have been deliberately targeted by exploration drilling, probably due to the uncertainties related to volume estimation and lack of precedents. As exploration of North Sea and other turbidite plays further matures such unconventional accumulations should receive increasing attention as they may provide significant upside potential for otherwise marginal accumulations.

Explorationists should thus include sand injectites as part of their interpretation mindset, both when exploring for the remaining oil in mature provinces, such as the North Sea, and when appraising less mature areas such as the NW European Atlantic Margin, offshore West Africa, the Gulf of Mexico and other deep-water provinces.

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