Seismic expression of large-scale sand remobilisation and injection in Paleogene reservoirs of the North Sea Basin and beyond

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Introduction

Clastic intrusions have been studied in outcrop for more than a century, but it is less than a decade since large-scale sand remobilisation and injection features were first recognised in seismic data from the Paleogene of the North Sea Central Trough. As even large-scale intrusion complexes can be subtle features on a seismic scale, the increasing recognition of such features can largely be attributed to the rapidly increasing quality and quantity of 3D seismic data covering almost the entire North Sea Central Trough. Once the diagnostic features of remobilisation and injection were recognized, a plethora of injection features were reported, both from core and from seismic data. Some degree of sand remobilisation, ranging from *in situ* liquefaction to large-scale fluidisation and intrusion, now appears to have affected many of Paleogene reservoirs in the North Sea Central Trough.

A series of case studies are being carried out. The focus of this paper is on the seismic expression of large-scale sand fluidisation and injection features, mainly with examples drawn from the North Sea (Figs 1-3). The increasing amount of 3D seismic and well data from the NW European Atlantic margin has led to an increased recognition of injection features, especially in the Faeroe-Shetland Basin. Although less well studied, we include examples from the Atlantic margin (Fig. 4) to show that large-scale remobilisation and injection are common phenomena, also outside the North Sea. Indeed, we believe that as new data become available, an increasing number of similar features will be reported from frontier basins along the North and South Atlantic and along other continental margins, and in older stratigraphic intervals.

Data

A large number of well logs and cores were available from both vertical and deviated exploration and production wells from several North Sea oil fields. The well data were integrated with conventional 3D and, in some cases, multi-component 3D seismic data from each field, thus providing a coherent database for studying remobilisation and injection features ranging from cm to km scale features. In some fields (e.g. Alba, MacLeod et al. 1999) the acquisition and interpretation of multi-component data has been instrumental in deciphering the subsurface expression of widespread fluidisation and injection phenomena, leading to substantial revision of reservoir models (Fig. 2).

Characteristics of remobilisation and injection

Large-scale fluidisation and injection features are typically encountered in association with deep-water sand reservoirs in the Paleocene and Eocene at subsurface depths of 2-3 km in the North Sea Central Trough and adjacent areas. The Paleogene North Sea reservoirs are typically associated with turbidite-systems, including turbidite channel-fills, scour-fills, overbank deposits and fans.

Injection features recognized in cores include: sandstones with deformed and upturned laminae, "giant pillars", homogenised sandstones and injection breccias. These features occur most frequently at boundaries between sandstone and shale units. Sand-shale contacts are not depositional but sharp, and the injection features often cross-cut bedding at high angles, sometimes leading to near-vertical contacts. The shale units may be within the reservoir (intra-reservoir) or post-date it. Sandstones subjected to fluidisation often have higher velocities and densities than undisturbed sands while the gamma-ray log is unaffected. It may thus be possible to identify fluidised sand units using the suite of gamma, sonic and density logs available from most exploration and production wells. Petrographical analysis of cores has shown that increased velocities and densities detected by the wireline logs may be caused by slightly lower porosity and tighter grain packing in the fluidised sandstone relative to the depositional units (Duranti et al. 2000).

Reservoirs characterised by large-scale fluidisation and injection are often notoriously difficult to image, even on 3D seismic data. However, recent acquisition of multi-component 3D seismic data using ocean bottom cable (OBC) technology have vastly improved the subsurface image of the Alba Field, leading to revised reservoir models and development plans (see Fig. 2; MacLeod et al. 1999). Hence, the application of OBC technology may provide the key to properly imaging injected reservoir sands elsewhere. In any case, it would seem that wide-angle stacks should be interpreted alongside the conventional 3D cube for improved reservoir imaging.

Interpretation of converted-wave seismic data reveal substantial modifications by remobilisation and injection of the original depositional geometry of the reservoir, some of which may also be visible on conventional 3D seismic or wide-angle stacks. These features include mounds, lateral wings, ridges and partly detached sand bodies, which cross-cut original stratigraphic relationships (Figs 1-4). The injected features interpreted on seismic data are often high amplitude or "bright" (Figs 3, 4). This could be related to higher impedance of the disturbed sands, relative to *in situ* sands and shales, confirming the well logs and core observations, but other factors such as pore-fluid or tuning effects could also be in effect. Hence, careful examination of the polarity of the seismic data in the reservoir interval and of the event in question should be performed when interpreting bright events. Seismic modelling of the sand-body geometries inferred from the seismic data could provide valuable insights regarding which scale of features that can actually be imaged by the seismic data. Few studies of this sort have been reported and seismic modelling will therefore be an area of further studies by our group.

Mechanics of remobilisation

The mechanisms controlling the processes of fluidisation and injection of sandy reservoirs are still poorly understood, but it is clear that fluidisation can often be related to the interaction of several processes. Early sealing of the sand unit by surrounding shales may lead to overpressure developing in the sands during subsequent burial. This process would be amplified by hydrocarbon charge, a process often invoked to explain sand injection. Once sufficient overpressure develops, the seal is breached and sands remobilised by fluidisation as the pore fluids are expelled into the surrounding shales. Association of some injected reservoir units with active fault zones seems to indicate that earthquakes may have triggered fluidisation and injection of these reservoirs.

Differential compaction across the sand unit may cause fracturing of the surrounding shales, especially upward propagating fractures at the edges of the sand body and downward propagating cracks over the top of the sand body, each controlled by the compaction-controlled curvature of the seal. Several cases are known where seismically resolvable sand-injection features are related to layer-bound polygonal faults within the surrounding shales. However, the interaction between the polygonal fault systems and forced folds and fractures caused by differential compaction across the sand bodies is still poorly understood and will be investigated further over the course of the project.

Significance of remobilisation and injection

In extreme cases of massive sand injection, the entire oil column may reside within the injected part, overlying the original depositional body. The recognition and quantification of injection features can thus be essential for reserve assessment and development planning. Even in cases where only minor injection has taken place, the recognition of the features may still be important, as fluidisation prior to injection may have affected the porosity and permeability of the *in situ* reservoir.

Many of the sedimentary structures in the Alba Field are typical of remobilisation by fluidisation and are associated with major sand injection features (Figs 1, 2). The scale of fluidisation (Fig. 1), inferred from cores and seismic, shows that this process was not simply a local bed-scale event that produced the characteristic dish structures and small pillars. Rather it seems that fluidisation affected large volumes of the reservoir, causing compaction and displacement of significant amounts of sand (Fig. 2). Sand body geometries such as revealed on Alba (Figs 1, 2) thus demonstrate the importance of identifying the characteristics of injected and remobilised sand units both from borehole and seismic data so that an integrated reservoir model can be developed.

Improved methods for characterizing large-scale fluidisation and injection are developed and used to provide a better understanding of the complexities of deep-water clastic systems, eventually leading to improved exploration and production models for deepwater sandstone reservoirs in the North Sea and of similar depositional systems elsewhere.

Acknowledgements

We acknowledge the financial support and cooperation by consortium members Chevron UK, Enterprise Norway, Kerr-McGee UK, Norsk Hydro, Shell UK and TotalFinaElf UK.

References

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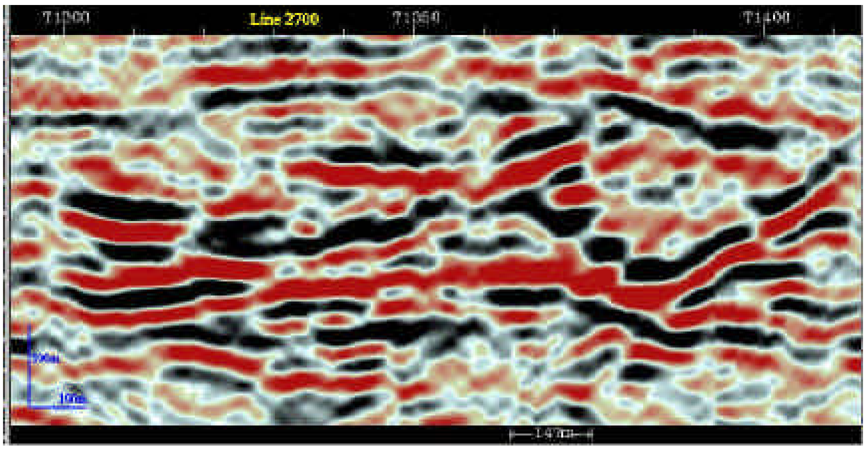

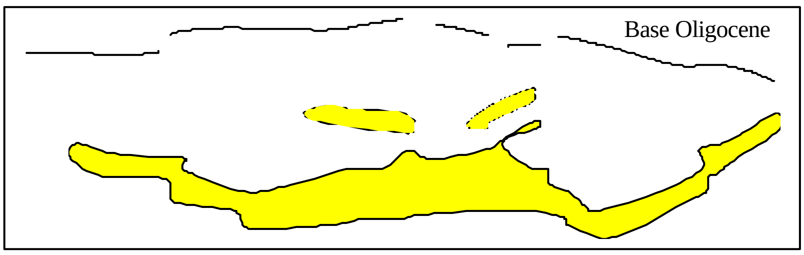

Fig. 1. Examples of injected and remobilised sand geometries imaged on 3D seismic data (data courtesy of Chevron UK and partners in the Alba Field).

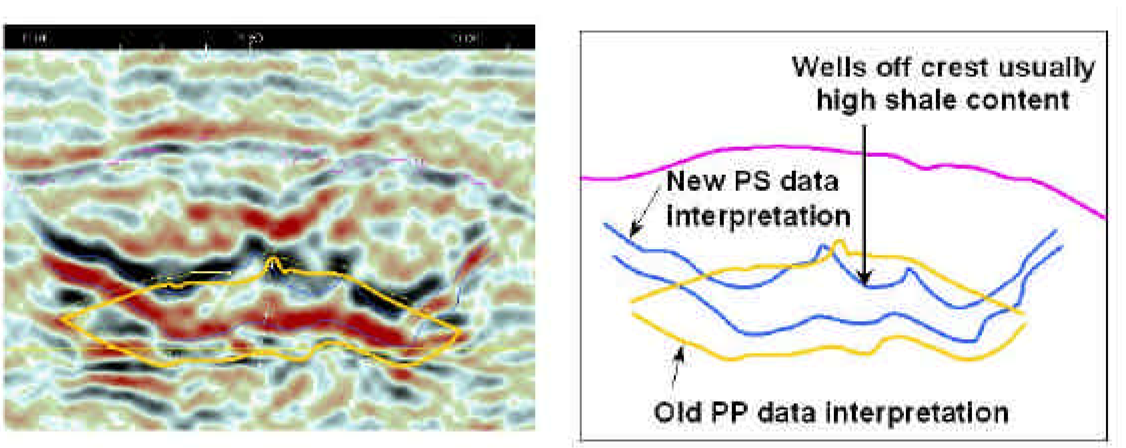

Fig. 2. Cross-section of main reservoir unit, Alba Field (courtesy of Chevron UK and partners in the Alba Field).

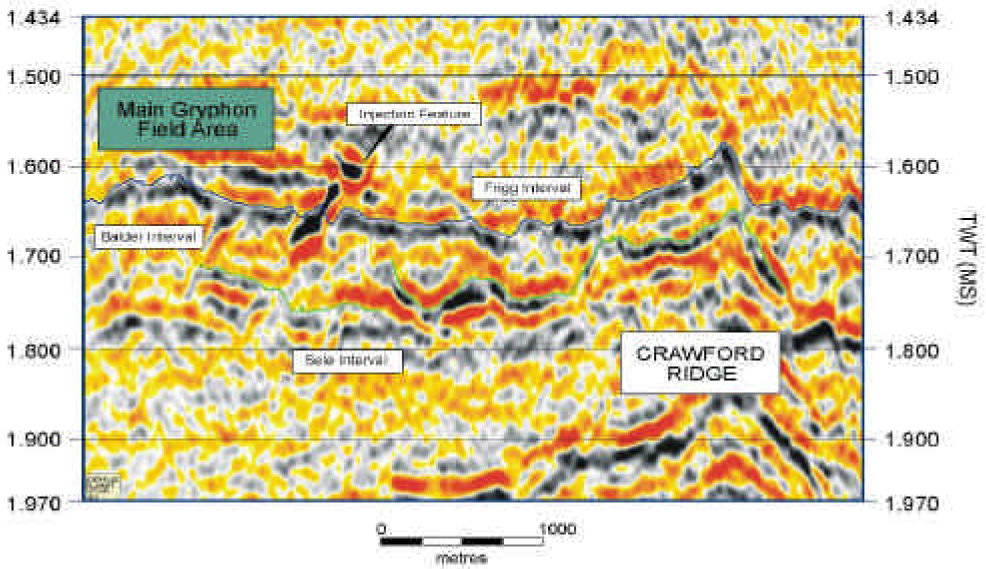

Fig. 3. Seismic example of high-amplitude events associated with sand injection (courtesy of Kerr-McGee UK; K. Purvis in publication).

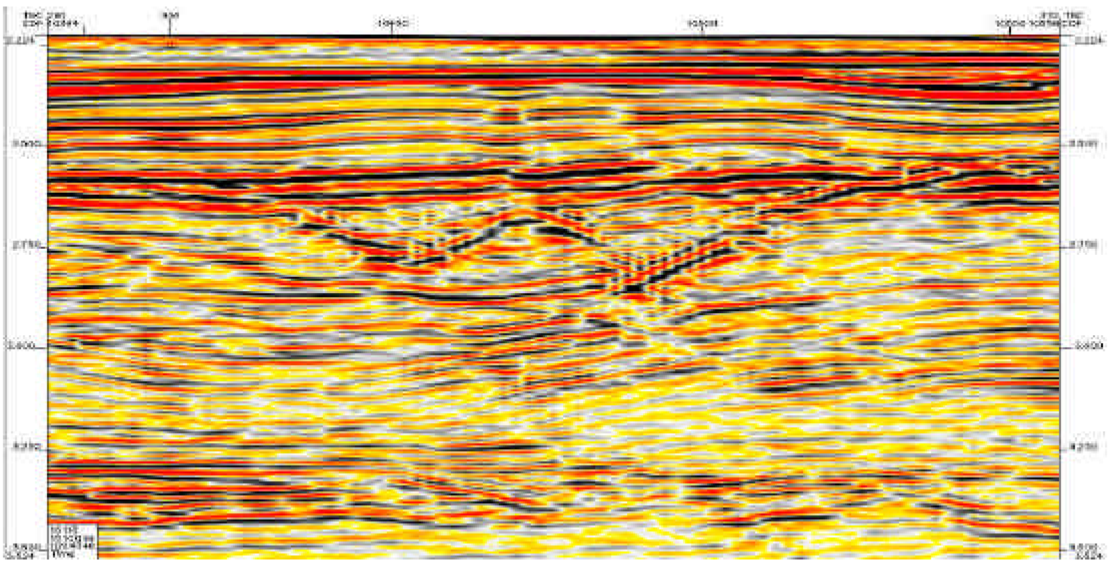

Fig. 4. Large-scale, high-amplitude injection features from the Faeroe-Shetland Basin (courtesy of PGS Ltd).