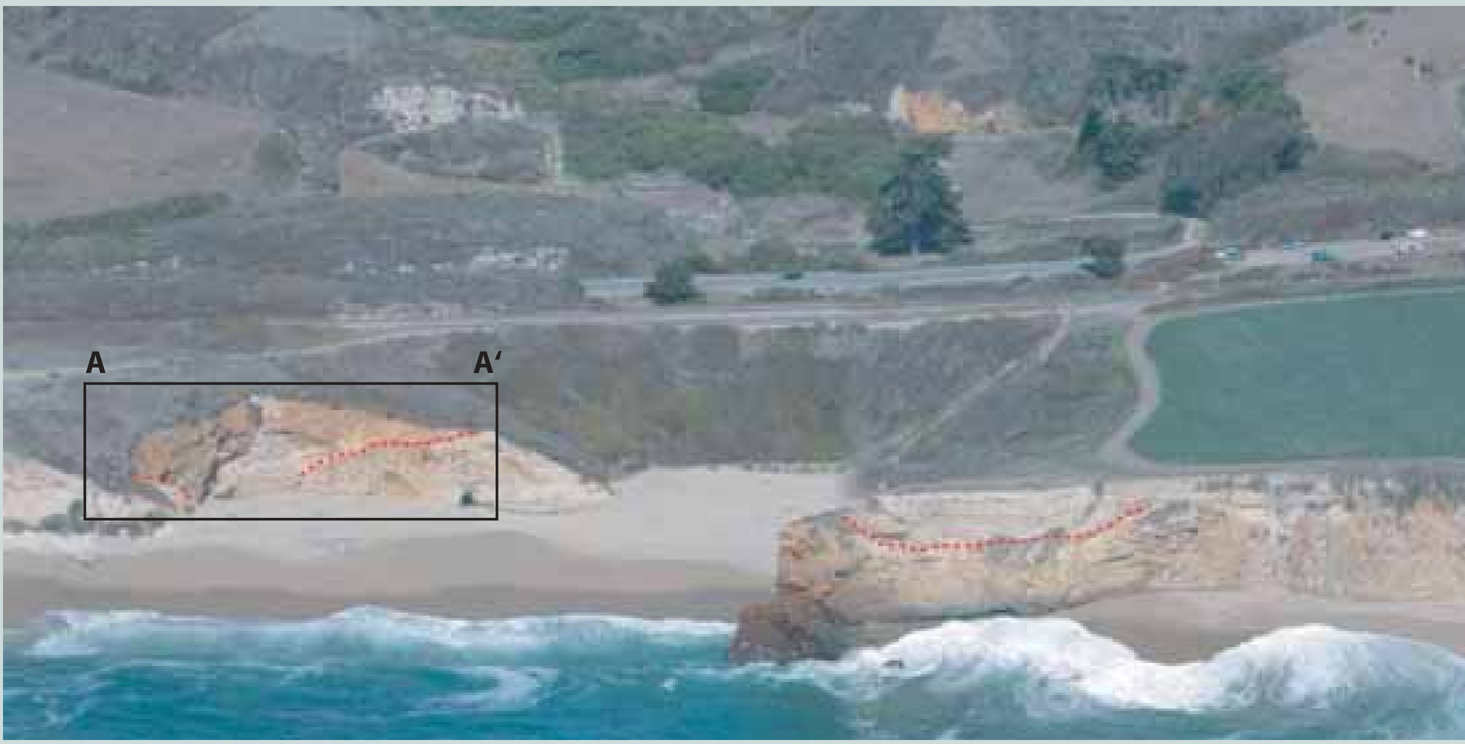
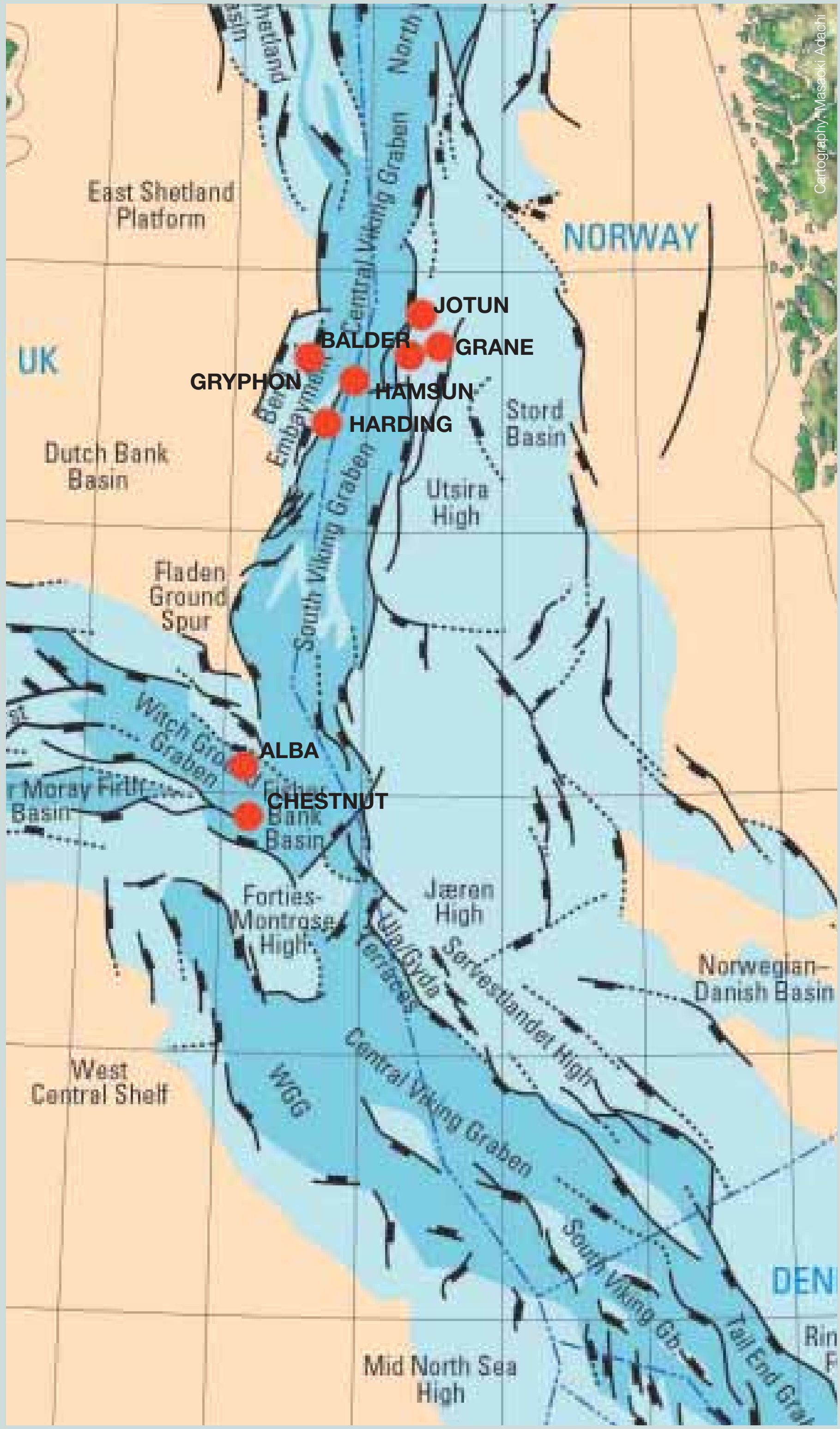
Sand intrusions reveal increased reserves



Sand injections through the Miocene Monterey Mudstones near Santa Cruz, California, are studied as part of a research programme supported by the oil industry to increase their understanding of these reservoirs. In outcrop, sand injectites are easily identified where they intrude finer grained strata and crosscut bedding. Also, when dykes cut through depositional units, they may be distinguished by the absence of depositional sedimentary structures and different grain packing. As part of an ongoing research programme field work was carried out in California this summer with the purpose of acquiring outcrop data for integration into seismic and reservoir models. Here we see the Yellowbank Creek sand intrusion complex immediately southeast of Davenport, California. Margins are dashed lines. Note the irregular (scalloped) discordant geometry of the roof and the discordant lateral margins. The sands are fine- to medium grained, stained by iron oxides and are not tar-saturated. Dolomite cement (grey) is abundant.



Oil fields of the North Sea with extensive remobilisation features in Paleogene strata include Alba (UK), Balder (Norway), Chestnut (UK), Grane (Norway), Gryphon (UK), Hamsun (Norway), Harding (UK), and Jotun (Norway). Sand injectites are thus recognised as important modifiers of reservoir geometry in many deep-water clastic systems. In particular they are found in the Paleocene and Eocene, Lower Cretaceous and Upper Jurassic of the North Sea and along the Atlantic margins of both UK and Norway. In several cases the reserves have been upgraded because of their recognition. Similar features associated with turbidites are also recognised offshore Angola and Nigeria in Tertiary strata. Their common occurrence suggests that they may also be present in other clastic provinces, such as the petroleum provinces offshore Brazil and in the Gulf of Mexico. Although best known in deep-water clastic systems injectites may be present in eolian dunes and deltaic facies as well.

Highly permeable sand bodies injected into low permeability shales may provide additional reserves to existing discoveries and fields if properly recognized. Such sandstones, a product of postdepositional remobilisation, may also constitute exploration targets in their own right when thick and laterally continuous. Improved understanding and detection of sand injectites has – in fact – led to a recent discovery.

Halfdan Carstens

"Sand injectites comprise dykes, sills and other more irregular features that form intrusive traps within otherwise impermeable shales," says Andrew Hurst, professor of production geoscience at the University of Aberdeen in Scotland, who is now heavily involved in research on these intriguing sand bodies that have been overlooked by the petroleum industry for such a long time.

"Sand injectites may combine with more conventional traps or occur in isolation. The reservoirs typically crosscut depositional stratigraphy and frequently form pay zones above horizons conventionally interpreted as top reservoir. This is why we need to pay more attention to them," Hurst explains enthusiastically. And he knows what he is talking about, having been involved as a consultant in a highly unusual exploration campaign in the Viking Graben of the Northern North Sea.

Andrew Hurst has put his hand on a near vertical dyke complex saturated with tar (black) that thickens up eventually spreading laterally on a palaeo-seafloor. The complex is within the siliceous mudstones of the Santa Cruz Mudstone Formation (Late Miocene) of the Monterey Formation in the Red, White & Blue Beach near Santa Cruz, California. Above his head the mudstone is extensively brecciated with a fine-to-medium sand matrix. To the right we see a complex swarm of high-angle dykes cut through the mudstones. Oil migrated into the sands after injection probably as low-gravity crude (Monterey source rocks generate 25 °API crude). The injection occurred during deposition of the Santa Cruz Mudstone in several phases separated by periods (100's of years) without extrusion.

"Recognition and evaluation of sand injectites can be vital for the appraisal and production of sandstone reservoirs affected by re-mobilisation and injection."

"A world first"!

"Large volumes of sand may be injected from depositional sand bodies. Calculations on North Sea data indicate that the pore volumes of such sand bodies may be several hundred million barrels. They thus represent a significant potential to proven reserves and may even constitute separate exploration targets in many petroleum basins. However, evaluation of reservoir quality is complicated by the unusual geometry as well as variable thickness, net/gross ratios and cementation. The lack

Dip section view of a sand injectite complex in Escapardos Canyon (Panoche Hills, CA). Orange arrow points to the deepwater clastic sandstones otherwise all sandstones are injected, a ca. 2 m thick composite sill (green arrows), diverse high-angle dikes and inclined sills (blue arrows) - all part of the Paleocene Moreno Formation.

of previous exploration of intrusive traps also hampers evaluation," Hurst says.

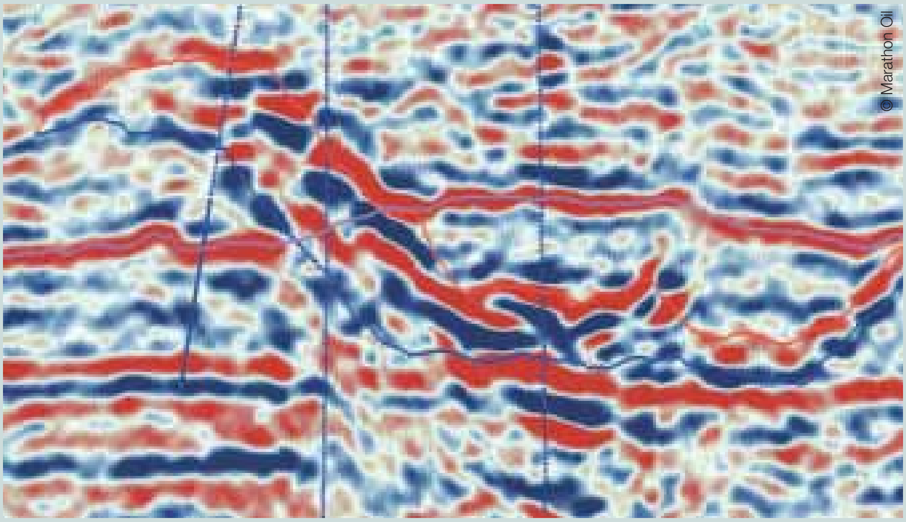
The dedicated geologist, with a long story to tell from more than ten years in Statoil and even more years as a professor, is now heading a research programme that focuses on acquisition of outcrop data and integration of those data into seismic and reservoir models. This work takes him to several places around the world where injectites can be studied in detail. The Miocene Monterey Mudstones near Santa Cruz, California provide good examples of sand injectites, which are easy to access, well exposed, and part of an active petroleum system. Here, dykes, sills and more diverse intrusive features, mud-clast breccias and sea-floor extrusions of sand all occur along the coast and are useful seismic-scale and intra-reservoir scale analogues for subsurface interpretation.

"Sand injectites often form highly permeable sand bodies within otherwise low permeability strata, which - when sufficiently large - form intrusive traps."

The ongoing research Andrew is involved in follows a two-year research programme that undertook subsurface examination of sand injectites and which was funded by an industry consortium. "The past programme encouraged pioneering exploration on the Norwegian continental shelf by Marathon who drilled the first deliberate exploration well into a sand injectite complex (Hamsun, 24/9-7, compare map). The well encountered an oil column that was greater than 100 m thick in sandstones," says Hurst.

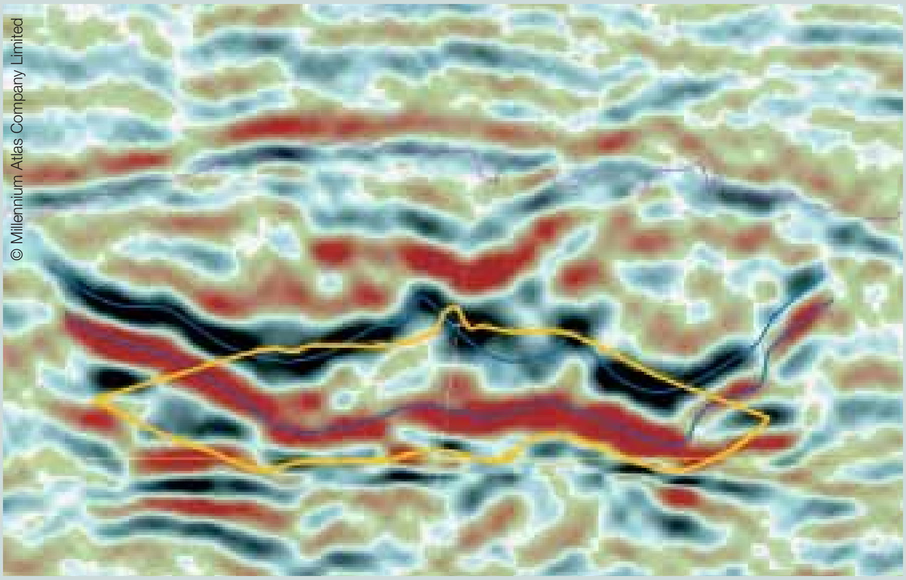
Bright seismic amplitude anomalies had previously been interpreted as a sandstone injection complex, but the prospect was considered too risky and not tested by the drillbit. Seismic modelling carried out by Marathon who acquired operatorship of the license in 2003 suggested that high porosity sandstones filled with oil caused the anomalies. One exploration well followed by three sidetracks proved high porosity sands and Darcy-range permeabilities.

"A significant oil discovery (in excess of

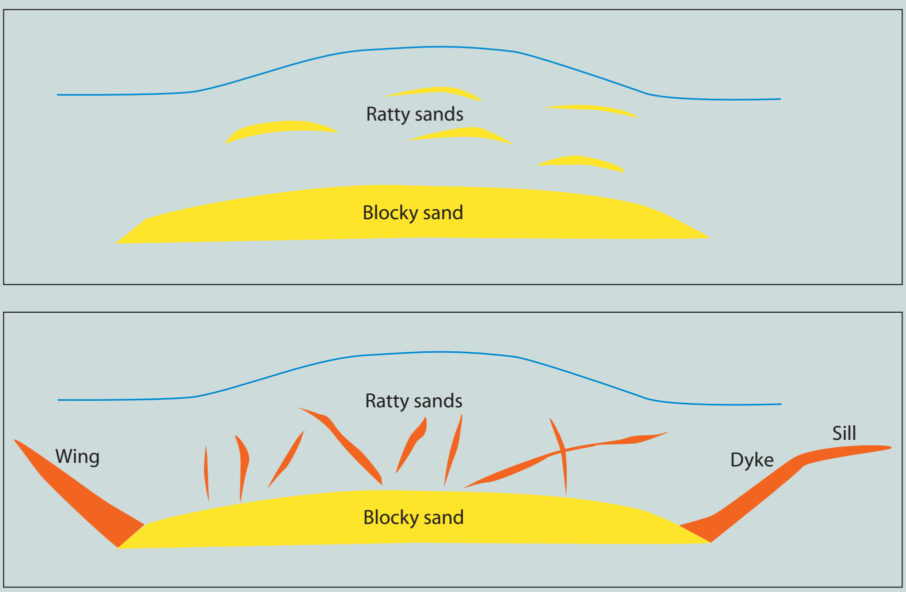


This seismic line through the Hamsun discovery of the Viking Graben, North Sea, shows where Marathon drilled the very first exploration well into a sand injectite complex. The pink horizon is top Balder Formation (top Paleocene) representing top of the massive deep-water sandstones. The red and blue horizons are the top and the base of the main sandstone in the injectite complex, respectively. The injection complex can be seen, but it is not possible to interpret internal geometries associated with the injected sands using these data.

Vertical dyke reaching the palaeo-seafloor forming a 1-1.5 m thick extrusive sand unit. Low-angle lamination represents units deposited around seafloor vents from which sand escaped (as fountains of fluidised sand) - large burrows, including escape burrows, are common throughout - grades up into siliceous mudstones.



Interpretation of the Alba field before (yellow) and after (blue) a 4C seismic survey conducted in 1998. The yellow colour shows the old conventional seismic-data interpretation, while the blue colour shows shear-wave seismic data interpretation with injected sands cutting across mudstones.



Models of sand distribution and geometries vary depending on data quality and interpretation mind set. The upper model shows a structureless sand distribution confined to an erosional scour with "ratty" sands on gamma-ray logs interpreted as thin-bedded turbidites in the overburden shales. The lower model shows a massive sand distribution with no apparent confinement and mounding due to differential compaction. The "ratty" sands are interpreted as sand injectites in the overburden shales, whilst wing-like reflections at the edges of the sand are interpreted as low-angle sand dykes and sills/extrusions. Over the past decade, increased quality of core and 3D seismic data has changed the interpretation of many fields of the North Sea Paleogene from the upper to the lower model.

100 MMB oil) had been made by an exploration drilling campaign which specifically targeted a large-scale sandstone injection complex, and we now know that the seismic amplitudes are associated with porous, hydrocarbon-charged injectites," says Hurst who also acted as a consultant to Marathon during exploration and appraisal of the prospect.

"We believe this represents a world first," he adds.

Unknown to petroleum geologists

Andrew Hurst explains that sand injectites have been known as a geological phenomenon since the early days of earth science. The first description that he knows of, is found in the *Transactions of the Geological Society* in 1827. The legendary British geologist Roderick Murchison then published a paper that describes the Kintradwell dyke in the Kimmeridgian shales of the Helmsdale Boulder Beds of northern Scotland.

"Outcrop examples of sandstone intrusions were also described around a century ago by various workers in California where the tar contained in some of them was worked commercially. The tar was a particularly important resource during the rebuilding of the streets of San Francisco following the 1906 earthquake," Hurst explains.

Sand injectites have only recently been recognised in the subsurface. "Petroleum geologists and engineers have been unaware of their significance as reservoirs until the 1990's when it became evident that numerous Palaeogene reservoirs of the northern North Sea have been subject to large-scale remobilisation and injection of sands. Their full significance in petroleum systems is, however, the subject of further research."

"Thanks to the improvement in the resolution and coverage of 3D seismic several deep-water clastic oilfields are now recognised as having substantial reserves in injectite facies."

"The reason can partly be ascribed to the fact that very few outcrop descriptions capture the same scale of features as identified in oil fields, even if they share many textural characteristics and geometries. Another reason is that their recognition in the subsurface is largely dependent on high quality 3D seismic, which have become abundant only the last 10 years or so," Hurst says.

One of the first detailed descriptions of sand injectites as a reservoir was made only some six years ago *(The Leading Edge, November 1999, p. 1306-1312)* by a team from Chevron and Schlumberger. Using ocean-bottom cables they acquired 3D shear-wave data over the Alba field in the

North Sea that led to the identification of large injected sand bodies at the margins of, and above, the main reservoir. In particular they noted "wing features" in the top sand reflector at the channel edges and occasionally over the central axis of the reservoir. Two wells were subsequently drilled based on the new knowledge. The first well encountered 150 m of oil-saturated sands within a post-reservoir shale section and produced up to 20.000 bopd. The second well showed that the wing in the western part of the field is 20 m thick. Both wells thus validated the presence of the wings.

These observations led the team to conclude that significant post-depositional deformation of the deep-water clastics had occurred. They hypothesized that reservoir sands had been remobilised and injected into the overlying shales. This work undoubtedly had a major influence on the economics of the Alba field development, if only because wells could now be drilled into sand-rich sections with far greater confidence.

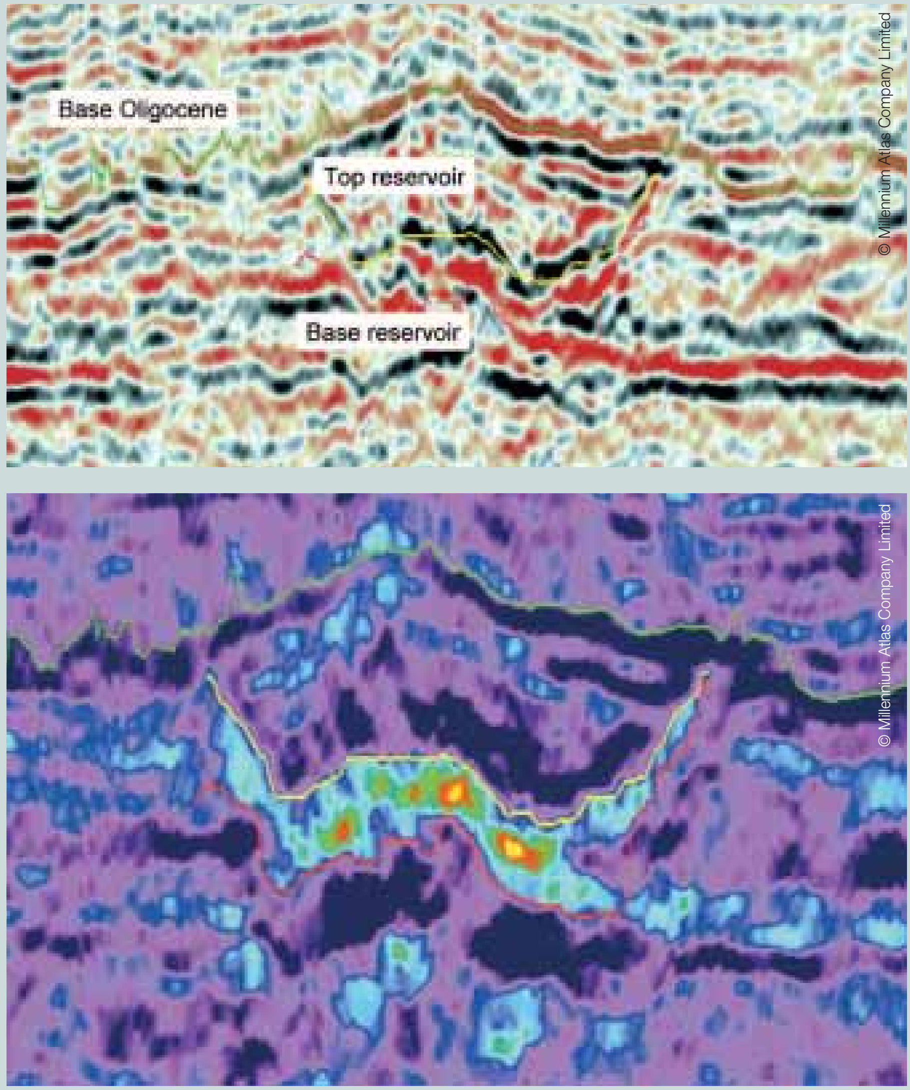
Spectacular images

The dimensions of injected sandbodies range from millimetre to kilometre scale. In outcrop and boreholes, observations are based on a much smaller rock volume than seismic data, but they give a higher level of detail. Seismic data, on the other data, give the possibility to study intrusion complexes that are tens of metres thick.

"The best-known injectite reservoirs are in Tertiary strata associated with turbidite reservoirs. Sand injections, however, also occur in a variety of sedimentary environments and from other stratigraphic intervals," says Hurst. "It is therefore likely that we will see a large increase in descriptions of such facies and reservoirs as the criteria for their identification in cores become more robust and high-quality seismic help to define them in new locations."

The sand injectites are similar in geometry to igneous intrusions, forming both laccoliths and dykes, and on the seismic data they have a distinctive appearance.

"Injectites that emanate from the edges of depositional sand bodies, sometimes referred to as "wings", are inclined (15-40°) sills that may be up to 25-30m thick and cross-cutting up to 200-250m of compacted strata. Laterally they may be extensive on a kilometre scale, and dykes may turn into sills. Wing-like reflections have been documented from a number of isolated



Multi-component seismic data show reservoir sands injected into higher levels in the Alba field in the UK sector of the North Sea. Oil-filled sandstones lying above the main reservoir are now known to be injected and remobilised sands from the main reservoir body.

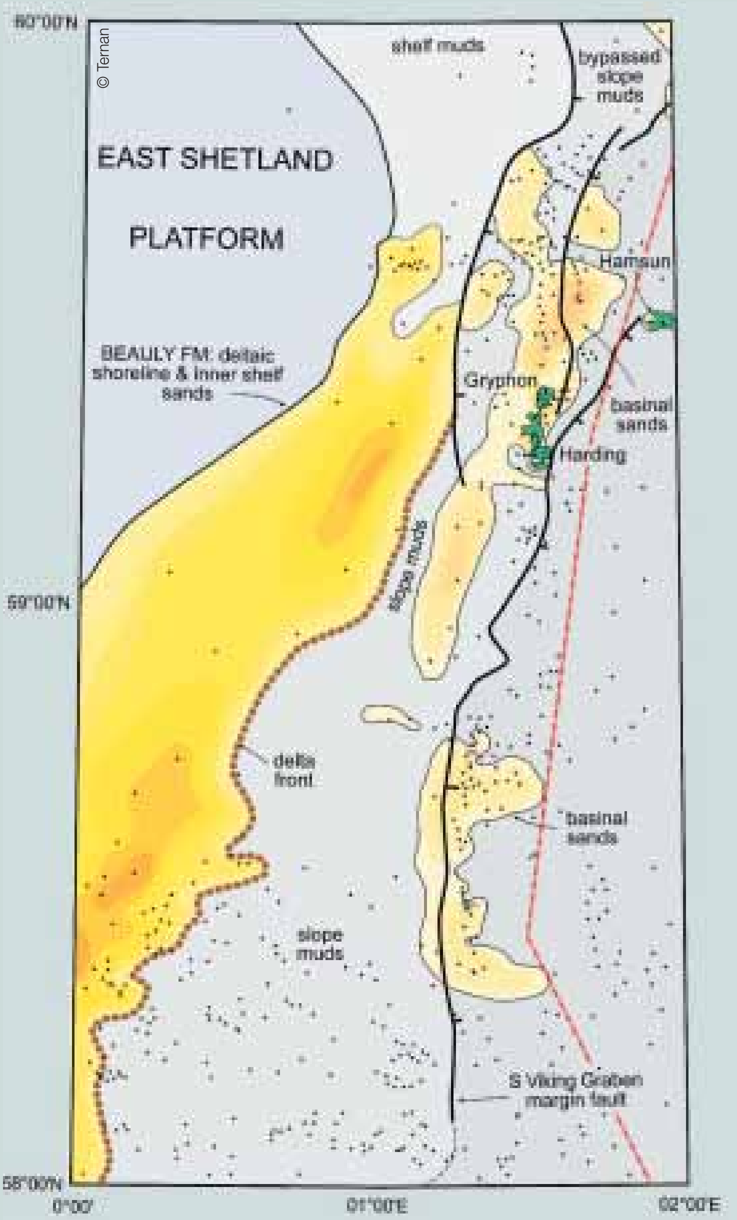
sandstone accumulations in the northern North Sea. Palaeo-seafloor extrusions may also have occurred," explains Hurst (compare photo page 17).

The other seismic-scale feature related to sandstone intrusion comprises V-shaped (2D) or conical (3D) anomalies that do not appear to be in connection with underlying sandbodies. In the northern North Sea this seismic signature is very common in the Lower Eocene, and wells penetrating them have had tens of metres thick sandstones. The seismic anomalies are thus interpreted to be sandstone intrusions fed by blow-out pipes originating from massive sandstones below. These intrusions are in the order of 100-300m height and 500-1500m in diameter, with flank dips around 15-45°.

"Shales into which sand has intruded have an irregular pattern on seismic images. We interpret this to reflect the irregular thickness distribution of the sand injec-

"The initial failure to recognise sand injections has caused major problems in the evaluation and development of several North Sea fields."

tites rather than folding or slumping of the shales. Cores taken within these shales and above turbidite reservoirs show the presence of thin-bedded, "ratty" sandstones as



Lower Eocene Balder Play Reservoir Distribution. Many of the basinal sandstone occurrences (Odin Sandstone Member) are now interpreted to be injectites sourced from underlying Palaeocene sandstones. This map is relevant for the Gryphon, Harding and Hamsun Fields, which are all shown on the map. Map from Ternan´s Regional Play Fairway Evaluation of the North Sea.

identified by the gamma-ray logs. We believe they represent sandstones intrusions rather than thin turbidites. Without cores, these sandstone units can sometimes be identified using dipmeter and image logs due to their discordant nature and cross-cutting relations with the encasing shales."

Difficult to detect

"Seismic resolution of injected sands with sill or dyke geometry is possible, providing the sand bodies are sufficiently thick to give a tuning response or discrete reflections from top and base of the body. We believe that sand injectites of the order of 10m thickness are normally resolved in many North Sea reservoirs of Tertiary age, even if intrusions thicker than a meter or so they can occasionally be detected by high quality seismic data," Hurst says.

"The limit of detection is strongly dependent on acoustic impedance contrast between sand and the adjacent fine-grained strata. Vertical to steeply dipping features can only be imaged directly under special geological circumstances. Estimation of their presence, size and distribution is therefore problematic. Mapping of sand injectites from seismic data provides a minimal estimate of the number and volume present. Based on observations in boreholes we have good reason to believe that their numbers are underestimated when applying only seismic."

Geologists interpreting seismic data of turbidite reservoirs may also encounter difficulties. As large-scale sand intrusions and associated withdrawal of sand from the source sandbody will modify the original geometry of the reservoir, interpretation of the top reservoir horizon will be complicated. It does not correspond to a stratigraphic surface, rather it jumps from "highs" to "lows" along the line and may cause difficulties when trying to find optimal location of production wells.

Changing mind-set

"When large sand injections are present, such as in Alba, Balder, Harding and Gryphon fields, they constitute targets for development wells, and early recognition of sand intrusions is important for optimal development planning," says Hurst.

"Early recognition of sandstone intrusions is a key factor in maximising exploration and production success in the deepwater sandstones of the North Sea. Explorationists in particular should take care in including sand injectites in their interpretation mind-set, and this also applies to other geological provinces with deep-sea sediments such as the West African Atlantic Margin," concludes Andrew Hurst.

Professor Andrew Hurst at the University of Aberdeen, Scotland, has an industrial as well as academic carrier. His main research areas today comprise sand injectites, deep-water clastic systems, non-destructive analysis of porous media and mineral-chemical stratigraphy (the role of climatic change on clastic composition and supply).