Large scale deepwater sediment remobilisation : examples from North Sea 3D seismic and outcrop

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ABSTRACT

The Palaeocene/Eocene to Mio-Pliocene sediments of the Central and Northern North Sea contain deepwater sediments with significant hydrocarbon reserves within submarine fan sands encased in mudrocks. Post depositional processes have significantly changed the original small and large scale geometry and reservoir characteristics of these deepwater sediments.

Examples of large scale remobilisation from 3D seismic, well and core data from the above intervals vary from cross cutting 10's of metres thick and 100's of metres in extent intrusions of sands, kilometer scale seabed pockmarks, sand mounds with kilometre wavelengths deposited between a mud mounded sea floor and syn to post depositional controlled polygonally faulted deepwater sands.

Outcrop analogues of large scale remobilisation are difficult to identify as the scale of these sandstone intrusion is often larger than the outcrop available. Within Upper Miocene Santa Cruz Mudstone, Santa Cruz, California exist one of only two kilometre scale sandstone intrusion complexes in the world. The intrusion of these sands is postulated to have been related to the expulsion of basinal fluids including hydrocarbons and related overpressure build ups, as proposed for several of the intrusive examples above in the Tertairy of the North Sea.

The geoscientist should be aware of the small to very large scale nature of sediment remobilisation which can significantly change primary depositional geometries and physical properties of deepwater sediments. These above examples of remobilisation highlight the great variation in reservoir character, which may significantly affect the petroleum exploration and development of such reservoirs. Ignoring such features will lead to incorrect reservoir modelling and subsequent exploration and development "surprises".

INTRODUCTION

This paper outlines examples of large scale remobilisation as examined from 3 D seismic datasets from Tertiary deepwater reservoirs of the North Sea.

Section 1 reviews previous works on large scale remobilisation and the processes which may be involved.

Section 2 documents a large scale intrusive complex in block 24/9 of the Norwegian Viking Graben (North Sea) in Palaeocene aged deepwater sediments of the Balder Formation.

Section 3 outlines interpreted large scale sandstone intrusions within UK North Sea block 21/4 and 5 of Lower Eocene age deepwater sediments.

Section 4 outlines Lower Eocene aged pockmarks of UK North Sea block 15/18 which occur within deepwater slope deposits.

Section 5 describes kilometre scale interpreted deepwater sand and mud mounds of the Lower to Middle Miocene Utsira formation in UK North Sea blocks 16/27, 28 and 29.

Section 6 presents the Upper Eocene Belton Member deepwater sands which are interpreted to have been controlled in their deposition by polygonally faulted lows and highs forming displacing the palaeo muddy seafloor.

Section 7 reviews a coastal exposure of a large scale sandstone intrusion complex which extends over a kilometre within Upper Miocene Monterrey diatomaceous shales, at Yellow Bank Creek, Santa Cruz, California.

Finally, section 8 summarises the potential effect large scale remobilisation may have on exploration and development of deepwater reservoirs.

1. REVIEW OF LARGE SCALE REMOBILISATION

Reservoir remobilisation can be defined as : "any comprehensive redistribution of reservoir units from their original depositional configuration due to pore pressure build up".

Small scale (mm to metre) remobilisation of deepwater sandstone reservoirs in the form of sandstone dykes and sills has been recognized in outcrop and in core since the 1900's (see review of sandstone intrusions in Allen, 19851). Large kilometre scale remobilisation of deepwater sediments has been rarely observed and only two documented outcrops exist worldwide ,(a) Ordovician sandstone intrusion complex of the Southern Front Range, Colorado, USA (Harms, 19652) and (b) Upper Miocene sandstone intrusion complex, Yellow Bank Creek, Santa Cruz, California, USA (Jenkins, 19303; Thompson, 19954; Thompson, 19995). Only recently has large scale remobilisation been recognised subsurface with the advent of 3D seismic. Dixon et.al., 19956 highlighted large scale injection and remobilsation of sands from the Forth/Harding hydrocarbon field reservoired in North Sea Tertiary deepwater sediments. Thicknesses of sandstone intrusions reach upto 10's of metres with lateral extent over 100's of metres. Sandstone intrusions also occur within similar aged Tertiary North Sea deepwater sediments of the Balder (Jenssen, et.al. 19937), Gryphon (Jaffri, 19938; Timbrell, 19939), and Alba (Lonergan and Cartwright, 199910) hydrocarbon fields.

It is important to note that these deepwater turbidite sands were deposited within extensive deepwater muds which were pervasively deformed by polygonal faults. Polygonal faults are a response of muds to expelling water in three dimensions almost immediatley upon deposition and during burial (Cartwright 1994a11, 1994b12, Cartwright and Lonergan 199613, 199714, Cartwright and Dewhurst 199815; Lonergan et.al. 199816). These faults on seismic data sets have a polygonal pattern in plan view, are spaced between 100 to 1000 metres apart and have displacements of between 10 to 100 metres.

Below are a series of large scale remobilisation examples interpreted from 3D seismic, well and core data from the North Sea (section 2 to 7) and an outcrop example from California, USA (section 8).

2. NORWEGIAN NORTH SEA BLOCK 24/9 PALAEOCENE BALDER FORMATION LARGE SCALE INTRUSIVE COMPLEX

Large and small scale sandstone injection features (discordant dykes, sills and clastic intrusions) are documented from 3D seismic, well log and core data in Late Palaeocene to Eocene sediments from Norwegian North Sea block 24/9.

The study area is located in the axis of the South Viking Graben, with Tertiary deepwater sediments supplied mainly from the west. Two wells in the block (24/9-5 and 24/9-6) encountered oil in massive sandstones of late Palaeocene/early Eocene age (Balder Formation), corresponding to a high amplitude response on seismic. These sandstones are confined to an isolated east/west trending fault bounded low, and vary from a few metres to 40m thick. Deposition from detached sand-rich debris flows or high energy turbidity currents is suggested.

Evidence for modification of depositional geometry is present at all scales. From seismic data, steeply dipping high amplitude continuous reflectors (10 to 50 msecs TWT/ 10-50 metres thick) can be followed from within the Balder, up along fault planes and into Eocene sediments above cross cutting up to 200m of stratigraphy at an angle of 10 to 30 degrees. The top of the Balder reservoir is complexly faulted, though many of these faults do not offset the base reservoir surface. Discordant sandstone dykes, shear fractures and compactional features in core suggest early sand remobilisation.

These steeply dipping high amplitudes originating from the Balder below are interpreted to be 10 to 50m thick sandstone intrusions. Injection is postulated to have occurred by expelling basinal fluids and hydrocarbons during the Eocene to Miocene, which built up overpressure in the isolated Balder age sands below, with overpressure being released during during fault movement.

The Balder discovery contains hydrocarbon reserves, but untested upside in the form of the injected sandstone high amplitude limbs could form a well-connected reservoir, cross-cutting stratigraphy, and increasing recoverable reserves. If successfully proven, field development would be optimised by locating producing wells in the higher injected portions, draining connected reservoirs in the Balder Formation.

3. UK NORTH SEA BLOCKS 21/4 and 5 LOWER EOCENE AGED LARGE SCALE SANDSTONE INTRUSIONS

Kilometre scale, Lower Eocene "V" shaped amplitude anomalies, have been recognised on 3-D seismic surveys from the UK Central North Sea. These features are interpreted as concave upward conical sandstone intrusions. They are typically circular to elliptical in map-view with diameters of single cones ranging from 0.5 to 2km. Their sides are 100-300m tall, and dip between 5 and 15 degrees (compacted). Intrusion width is 10 to 50 msecs which calibrates to 10-50 metres of sandstone exhibiting a blocky, low gamma ray character on wireline logs. The conical sandstone geometries can be isolated or developed as compound structures amalgamated in clusters covering hundreds of square kilometres. These amplitudes match the geometries of polygonal faults which pervasively deform the encasing Lower Eocene muds.

We considered several possible genetic models for these structures, including palaeo-pockmark craters, collapsed gas hydrate diapirs, and even isolated fan channel ribbon deposits. However, the preferred explanation is that upward migration of thermogenic methane generated from Jurassic source rocks released during earthquake or by auto-triggered failure of pressure seals led to inflated fluid pressures in isolated Palaeocene or Eocene deep water sandbodies. Catastrophic pressure inflation (internal blow-out) then led to large volume liquefaction of the sands, and upward conical injection which exploited pre-existing fault and fracture networks (polygonal faults), in the low permeability claystones of the Lower Eocene. We believe that these Lower Eocene intrusions are the largest reported subsurface examples of clastic remobilisation, which by their very scale may have been overlooked or misinterpreted in outcrop in other basins.

4. UK NORTH SEA BLOCK 15/18
LOWER EOCENE AGED LARGE SCALE POCKMARKS (Cole, D, 199817)

A detailed 3D seismic interpretation has identified crater-like structures in the Paleogene sediments of block 15/18, Outer Moray Firth, UK North Sea. The structures range from 500 metres to 4 km in diameter and are between 50 to 200 metres deep.

The structures are confined to one stratigraphic level, at the top of the early Eocene Balder Formation, and are restricted to an area of 15 x 15 km square within the available 3D seismic coverage.

The craters appear to cut down into the top Balder Formation on 3D seismic data. They have seismically chaotic infill and mounded overlying reflectors. Planar high amplitude "wings" are located on the flanks of several of the structures.

Well data suggest that the structures are themselves sand-filled, but occur within an argillaceous and tuffaceous unit. A 100m thick mudstone unit overlies the structures. The planar "wings" appear to be intruded sandstone dykes.

Shallow gas eruptions on the early Eocene seafloor is the most likely mechanism for the formation of the craters as explosively formed seabed pockmark craters. The gas may have been sourced from deep Jurassic or Carboniferous sediments within the Witch Ground Graben, or it could have originated in the Palaeogene delta sediments within the study area.

Similar structures may prove to be effective hydrocarbon plays. The structures are large (100 x 106 m3 gross volume) and appear to be infilled with clean, massive sand. The suggested mechanism requires large-scale early Eocene hydrocarbon migration. If correct this is evidence of both a mature source and effective migration pathway. Migration of hydrocarbons would need to continue after deposition of the top seal to allow any entrapment. The overlying muds provide a competent top-seal to have forced sandstone diapirism. These muds may still act as an effective top-seal in restricted areas.

5. LOWER TO MIDDLE MIOCENE
UTSIRA FORMATION KILOMETRE SCALE SAND MOUNDS, UK NORTH SEA BLOCK 16/27, 28 and 29

The Lower to Middle Miocene (Utsira Formation) of the UK North Sea blocks 16/27, 28 and 29 contain elliptical to circular mounded features, 1 to 2km wide, 0.5 to 10km long with a vertical relief of 50-100 metres.

They onlap a muddy strata below of Oligocene age, have flank dips greater than 7 degrees (compacted) and are formed of massive sands as noted from well control. These mounds occur over 10's of thousands of square kilometres of deepwater basinal shales of the Central North Sea.

The Utsira sand mounds are interpreted to be lowstand turbidite sands sourced from marine sands to the North in the Northern North Sea (Gregerson 199718, 199819), some 300 km away. These sands deposited onto a mud mounded sea floor with kilometre wavelengths. Anketell et.al. 197020 predicted such mounding within muddy substrates. Similar geometries have been noted by Davies et.al. 199921 within the Oligo - Miocene succession of the Faeoroe-Shetland Trough and Vogt (199722) in Pliocene sediments of the Norway Basin.

6. UPPER EOCENE BELTON MEMBER DEEPWATER SANDS SYN AND POST DEPOSITIONALLY POLYGONAL FAULT CONTROLLED, NORWEGIAN NORTH SEA BLOCK 24/9

Upper Eocene deepwater turbidite sands (Belton Member) of Norwegian offshore block 24/9 are expressed as a high amplitude reflection on 3D seismic data on a low amplitude palaeo sea floor of mud. Well data calibrates these amplitudes as blocky sands between 0 to 100 metres thick. These turbidite sands have been compartmentalised by polygonal faults which pervasively deform the muds. Amplitude maps and well data indicate that the sand is preferentially concentrated in the polygonally faulted lows on the Upper Eocene surface. These polygonal faults have fault displacements upto 300 metres in extreme cases, but more commonly between 10-50 metres and spaced 100 to 1000 metres.

The preferred interpretation is that the Belton Member sands deposited as deepwater sands onto a polygonally faulted palaeoseabed, which concentrated deposition of sands within the downthrown lows.

7. UPPER MIOCENE LARGE SCALE SANDSTONE INTRUSION COMPLEX, SANTA CRUZ, CALIFORNIA, USA

Giant scale sandstone intrusions are exposed on the coastline North West of Santa Cruz, California. They are the largest scale clastic intrusions in the world.

Sandstone dykes and sills of between 1cm and 300metres width, intruded into Upper Miocene diatomaceous mudstones, probably as a function of minor Pacific Plate reorientation at 4Ma (Casey Moore pers.comm. 1999). The intrusion is related to movement along a series of wrench faults at this time, part of the San Gregorio/San Andreas fault zone (Casey Moore pers.comm. 1999). The dykes and sills in outcrop are fine to coarse grained poorly dolomite cemented clean massive sandstones. The sandstone is often partially stained with degraded oil which at Yellow Bank Creek, the site of a 300m wide sill/dyke, display as complex banding and balls/pillows of migrating hydrocarbons. These giant scale clastic dykes and sills may have been associated with migrating hydrocarbon fluids, expelling from offshore basins into this regionally higher, basin margin position.

8. EXPLORATION AND DEVELOPMENT ISSUES RELATED TO LARGE SCALE REMOBILISATION OF DEEPWATER RESERVOIRS

Interpretation of deepwater sandstone reservoirs is normally based on the interpretation of reservoir geometry that has a primary depositional origin. However, seismic and core evidence from isolated deepwater sandbodies in the Palaeocene and Eocene of the North Sea and the Californian field analogue reviewed above shows that original depositional geometries can be significantly modified by sub-surface remobilisation of sands by processes related to elevated pore fluid pressures which may involve hydrocarbons including gas. Important points to note regards large scale sandstone remobilisation are:

(a) Post depositional remobilisation of deepwater sediments is an important element in reservoir interpretation and modelling.
(b) Remobilisation involves in situ, higher pore pressure related processes such as fluidization and liquifaction of porous, poorly cemented sandstones at some stage during burial and reconfiguration of the original depositional geometry.
(c) Remobilisation changes reservoir properties and geometry: reservoir characterisation must be approached with this in mind.
(d) Failure to identify remobilised reservoirs prior to completion of the reservoir model will lead to unexpected results during development drilling.
(e) Large scale intrusion complexes may be related to tectonic activity and related flow which may also be associated with the migration of hydrocarbons from basinal kitchen areas. The presence of gas may be a large factor in heightened pore pressures associated with intrusions.
(f) Relationships to active faulting and folding such as large scale polygonal faulting of clay dominant systems may affect primary deposition of deepwater sand reservoirs and significantly change final reservoir geometry.
(g) Geometry of typical dyke-sill complexes is highly variable and complicated.

Wide varieties of geometries exist, from simple vertical dykes and horizontal sills to more complex sill-dyke geometries with conical, rectilinear or radial patterns, sea floor mounds, and pockmarks.

Large scale deepwater sediment remobilisation is a poorly documented and understood phenomena. The field geologist, seismic interpreter and petroleum geologist should bear in mind the scale and likely reconfiguration remobilisation may have on deepwater sediments in outcrop, well and seismic data. Incorrect recognition of remobilised sediments may for the petroleum geoscientist lead to subsequent exploration and development "surprises".

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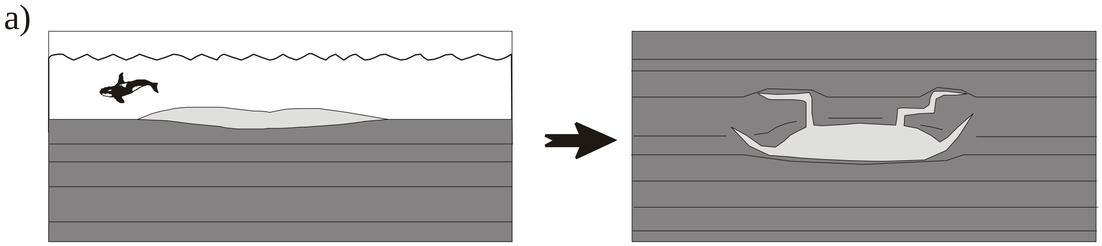
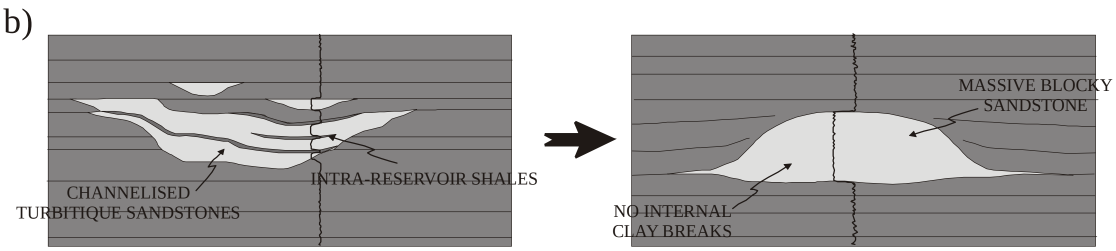
Examples of remobilisation affects on deepwater reservoirs

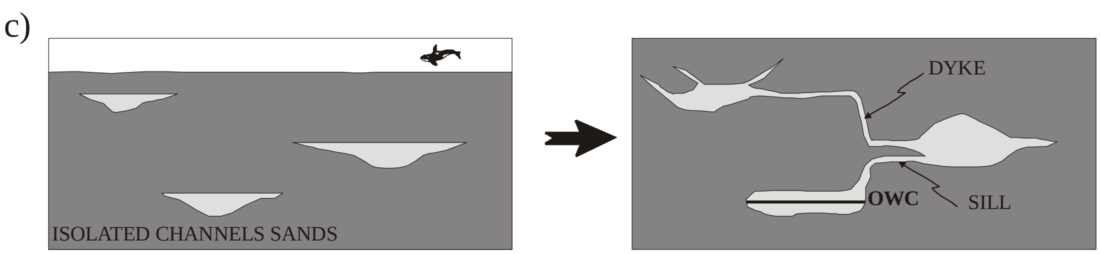
DEPOSITION | AFTER REMOBILISATION



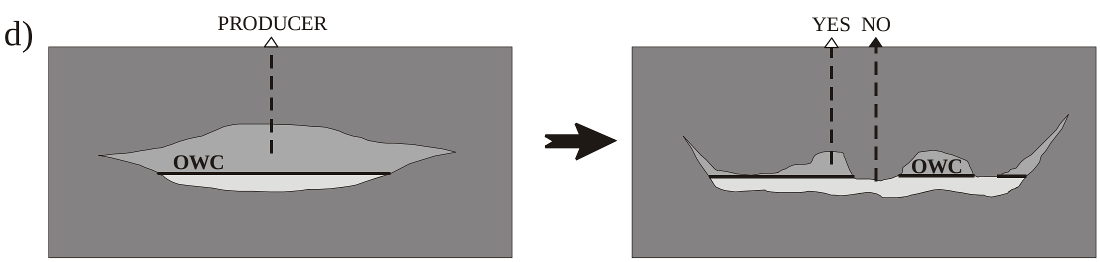
CHANGE IN RESERVOIR GEOMETRY



CHANGE IN RESERVOIR PROPERTIES

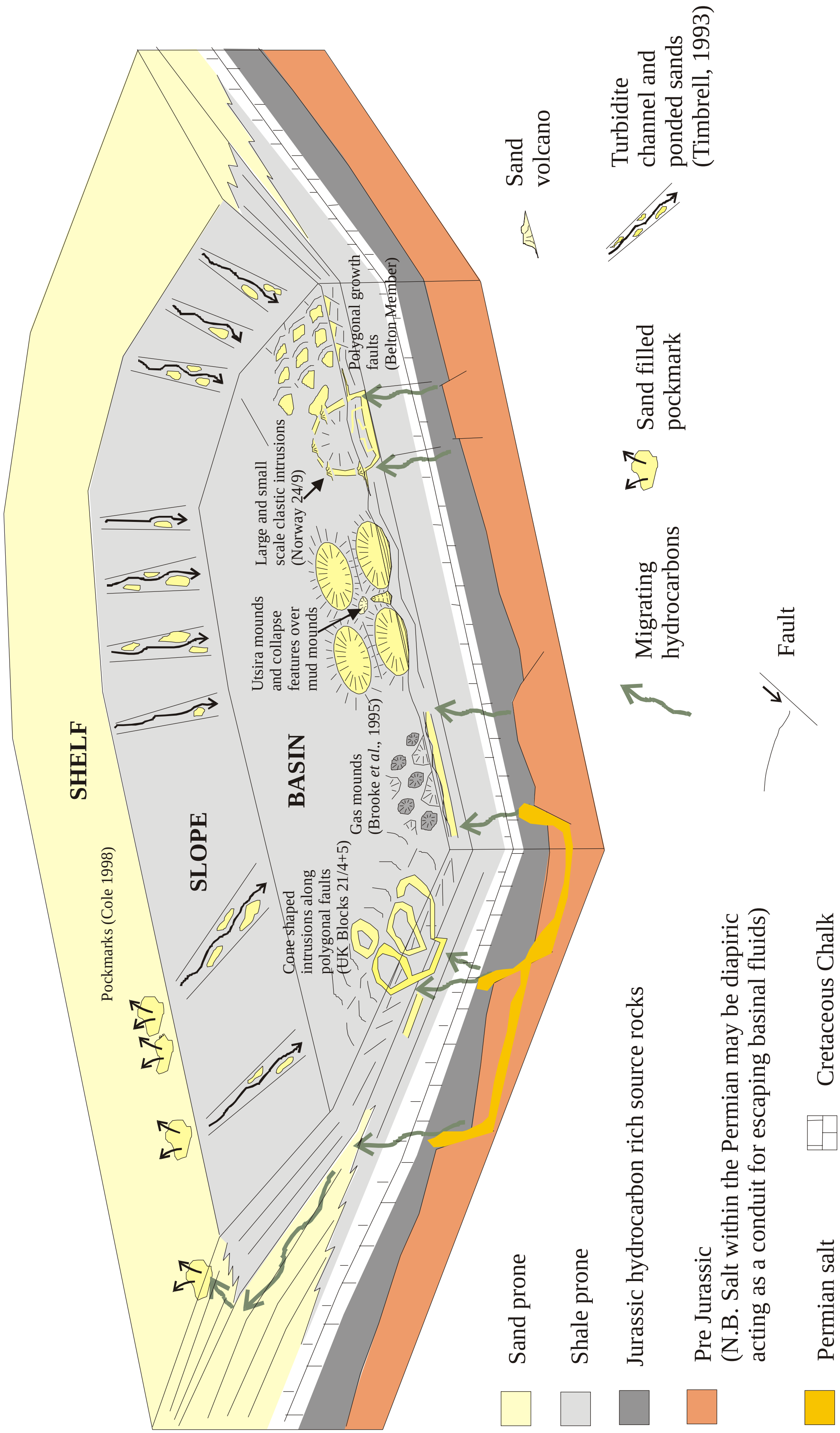


CHANGE IN CONNECTIVITY OF ORIGINALLY
ISOLATED RESERVOIRS

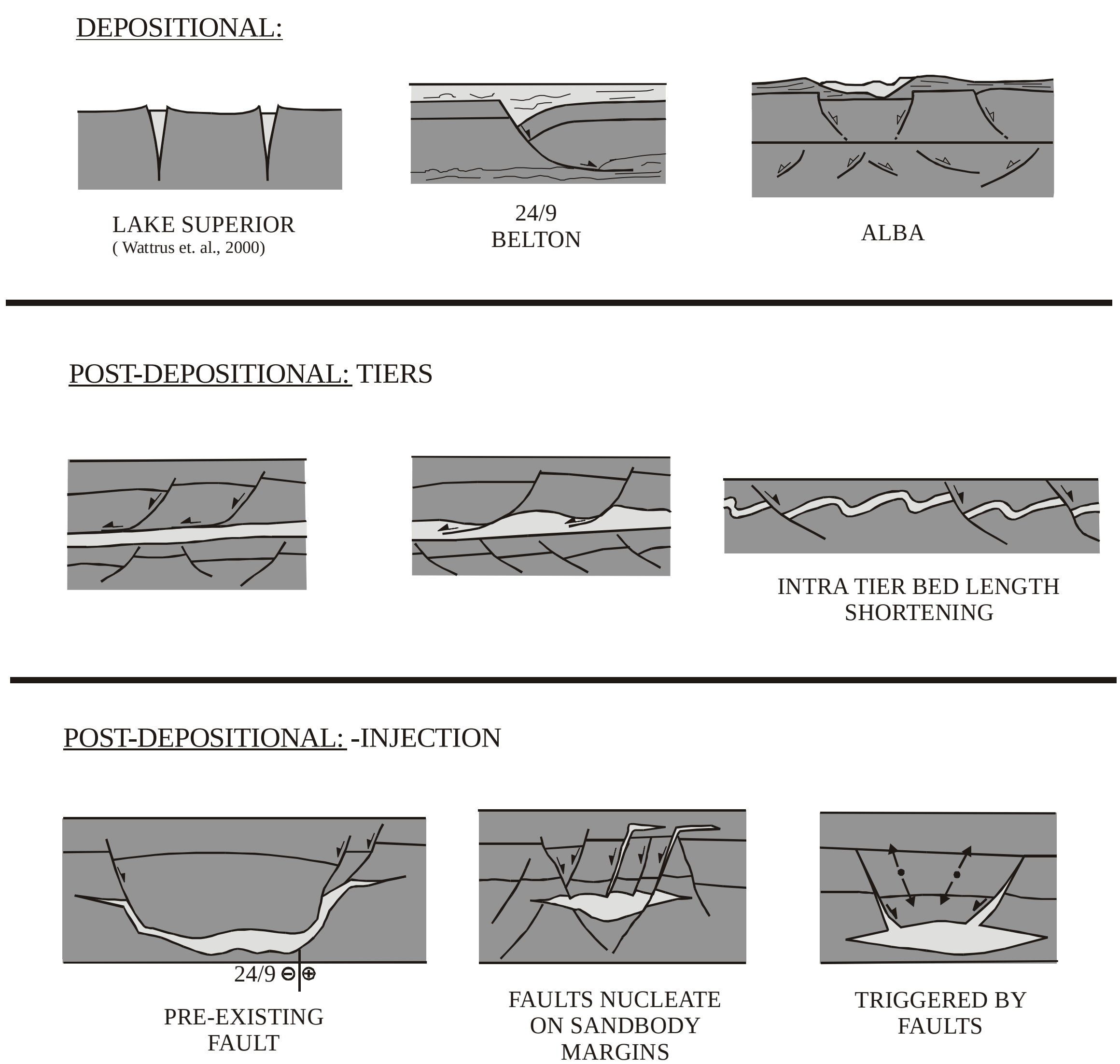


CHANGE IN TOP RESERVOIR SURFACE
AND IN RESERVOIR VOLUMETRIES

Model of large scale remobilisation features in the Eocene to Miocene of the North Sea



Impact of polygonal faulting on reservoir geometry (Cartwright et. Al., 1999)



Location of 2D and 3D seismic datasets used in this North Sea study.
(partly from PESGB, 1997; Jones et.al. 1999; Pergrum and Spencer, 1990)