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Relationship between bowl-shaped clastic injectites and parent sand depletion; implications for their scale invariant morphology and composition

Abbreviated title: Bowl-shaped injectites and depleted parent sand

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Abstract

3D seismic reflection data provides a means to assess the impact of injection on parent sands, and to quantify the character of the resulting injectite networks. The morphology of a series of large injectite structures hosted in the Palaeocene Lower Lista Formation were mapped using broadband 3D seismic data from the North Sea to investigate their relationship with parent sands. Fourteen bowl-shaped structures were identified within the Lista Formation in the study area (60-85 m in height, and 200-900 m in width). Sand is absent (below resolution) below these large-scale bowls, suggesting that the parent sand is the underlying Maureen Formation and sand 'welds' formed, rather than sand-prone channelised deposits within the Lista Formation.

Identification of injectite networks can be ambiguous, which impacts geological model development. Observations from exhumed systems and core, offers high resolution insights into the complexity of injectite networks. To advance our understanding of this scale gap, we argue for injectites being scale invariant in their shape and grain-size. This permits the application of outcrop-scale knowledge to seismic-scale interpretation. The demonstrable depletion of parent sands, and their scale invariance, can be applied to basin-fills worldwide to reduce uncertainties of the impact of sand injectites on hydrocarbon reservoirs.

Keywords: clastic injectites, dykes, sills, North Sea, scale invariance

Clastic injectites are the products of the forceful intrusion of sediment-rich flows into a host lithology (Jolly and Lonergan, 2002). The source of the intrusive material therefore, must undergo some form of sand depletion (Løseth *et al*., 2012). In core, outcrop, or seismic datasets it is challenging to associate injectite networks with their parent sand unit (e.g. Cobain *et al*. 2018) unless the connection is observed directly, and even more difficult if the parent body is partially depleted of sand. In the subsurface, identification of injectites and their parent sand is important for modelling fluid flow pathways between bodies of sand, and prediction of the reservoir quality of the injectites.

Here, we present a case study of clastic injectites and an associated potential area of sand depletion of the underlying stratigraphic unit, from the North Sea. Using a high resolution broadband 3D seismic dataset offers the opportunity to map injectite bodies, identify the likely parent sands, and to quantify their morphology and dimensions. The ability to map and quantify the large-scale injectites in 3D seismic data is an advantage over exhumed injectites, at outcrop (2D) and in core (1D). However, these data illustrate that there is both a far greater complexity in injectites than is often accounted for, and that they occur over several orders of magnitude. From this, we argue that in terms of geometry, injectites might be scale invariant in form and grain-size. Therefore, injectite geometry can be compared between systems. If there is scale invariance of injectite geometry this could improve reservoir modelling and the appropriate use of outcrop analogues.

Our aim is to map a series of injectites within the study area and consider their origin and sub-seismic characteristics. To meet this aim, the following objectives were addressed: i) documentation of the dimensions and shapes of injectites within the study area, ii) discussion of the timing and parent sand for the injectites, iii) consideration of whether injectites can be scale invariant by scale and composition, and iv) discussion of the implications of scale invariance on the use of outcrop analogues for injectites identified in the subsurface.

Geological setting

The North Sea case study area is composed of Palaeocene sediments that onlap Devonian basement and Late Cretaceous/Early Palaeocene chalk landward (Fig. 1) (Ahmadi *et al*., 2003). The lowermost Palaeocene sands are interpreted to be a series of massive, stacked, submarine channel and fan deposits (Maureen Formation; Mudge and Copestake, 1992; Mudge, 2014). Sands were fed via deltas and through slope channel systems from the north-west (Galloway *et al*., 1993) to a submarine fan. A thick (>600 m) hemipelagic mudstone succession (Lista Formation; Ahmadi *et al*., 2003) directly overlies the submarine fan and channel-fill sands, which formed during a period of relative sea-level rise. Located within these mudstones are a series of sand-prone channelised systems (Ahmadi *et al*., 2003). Injected and remobilised sands have been interpreted in the Lista Formation mudstone in many locations in the North Sea (e.g. Cheret and Carrillat, 2004; de Boer *et al*., 2007; Satur and Hurst, 2007; Kilhams *et al*., 2012). This study focuses on the architecture and source of clastic injectites in the Lower Lista Formation that directly overlies the Maureen Formation (Fig. 1B).

Methodology

Seismic mapping

The study covers a 5.75 km long, and 2.12 km wide (~12 km^2) sub-area of a high resolution 3D broadband seismic dataset, focussing on the Lower Lista Formation (Figs. 2A and 2B). The advantage of using broadband seismic data (or multi-sensor towed streamer technology) is the improved imaging of complex geometries, where it is possible to image Lista sandstone with higher frequencies and less sidelobes within the data, resulting in a more accurate interpretation (Østmo *et al*., 2014). The 3D broadband seismic survey has been time migrated with a standard anisotropic 3D Kirchhoff migration, was interpreted with in-line (IL), northwest-southeast orientation, and cross-line (XL), northeast-southwest orientation, and has a line spacing of 6.25 metres by 6.25 metres. A positive peak event (blue-black reflection) represents a downward increase in acoustic impedance whereas a negative trough (orange-red reflection) represents a downward decrease in acoustic impedance (Figs. 2C – 2F).

In the study area, reflections are more brightly imaged on the near angle stack (5°-17.5°), and were chosen for mapping. Mapped sands are penetrated directly by two vertical wells allowing them to be calibrated with the well logs (Fig. 3). Initially, the base of the sand bodies were mapped on every 16th IL and XL (100 m) and then from the grid created by this method every IL and XL was mapped where correlating between lines was problematic. Arbitrary lines were used where correlating between adjacent lines was ambiguous. Mapped sands crosscut stratigraphy, display both low and high angles of dip (defined as <20° and >20° respectively (Hurst *et al*., 2011)), and form bowl-shaped structures in 3D (Fig. 2). A major uncertainty with mapping injectites is that steeply dipping injectites (usually >60° (Jackson *et al*., 2011)) are not imaged on seismic data. However, because the dataset used in this study is of such high resolution, it is possible to infer whether an absence or break of seismic reflection is due to steeply dipping sand units. The complicated nature of injectite geometries, which locally includes the separation of a single mappable sand body into several thinner sand units on different stratigraphic levels, can produce a chaotic seismic response. Where this occurred either the brightest reflector was selected, or when no obviously bright reflector was present the lowermost reflector was selected (e.g. Fig. 2F).

Results and analysis

Seismic mapping

Fourteen bowl structures were mapped in detail over the ~12 km^2 study area, including bright reflections interpreted to be sands that connect to, or sit in-between, bowl-shaped structures. These structures are shown to crosscut stratigraphy at high angles (Fig. 2C-F) and internally have chaotic seismic response. After being mapped in 3D, 2D seismic profiles were taken at intervals of 50 m along both ILs and XLs for quantitative analysis (Table 1); some results are displayed as crossplots (Fig. 4). The key geometric parameters measured for each individual bowl include: i) plan view area as an aerial parameter (m^2), defined where the steeply dipping sandstone bodies pass abruptly into sills concordant with host strata; ii) height of bowl, defined as the vertical extent (m) from the base (lowest depth) to the abrupt change between steeply dipping side and shallowly dipping sill; and iii) the width of each bowl through both IL and XL sections, defined as the horizontal extent (m) along both IL and XL inside the aerial extent of the bowl (Table 1). Measurements provided have an uncertainty of ±6.25 m horizontally (bin spacing) and vertically of ±12 m (vertical resolution). Internal sand geometries and sand thicknesses are difficult to estimate because well calibrations show these are likely clustered zones of thin sands (Lonergan *et al*., 2007) as opposed to a single, thick, high net-to-gross body (Huuse *et al*., 2004; de Boer *et al*., 2007). Most of the bowl structures are between 60 and 85 metres in height. Maximum measured widths are between 200 and 900 metres (Fig. 2), with an average width of 574 metres. The vertical distance between the top of the Maureen Formation sandstone and the base of the lowermost section of each bowl ranges from zero (bowl 8a in contact with Maureen Formation; Figure 2D) to 89 metres (bowl 9). There are 2 distinct stratigraphic horizons above the Maureen Formation along which sands abruptly change from steeply dipping and discordant to concordant with stratigraphy (Figs. 2C and 2D). Quantitative data show that the degree of variability between the bowls is low to moderate. There is a strong correlation between the width and height of bowl structures (Fig. 4B). These sands are interpreted as clastic injectites due to their geometry (bowl-shaped and cross-cutting stratigraphy at high angles) and apparent relationship with underlying sand unit. Sands at high angles to stratigraphy have recently been described by Totake *et al*., (2018) where sand slices were mapped along thrust fault planes; in cross-section there is some resemblance to sands in this study at high angles to surrounding strata. This, however, is discounted as a possibility as mapped sands herein form bowl structures in 3D, and stratigraphy either side of the sands is not displaced.

Discussion

Source of North Sea case study injectites

The parent sand of these injectites is a source of debate; the two possibilities are either the Lista Sandstones, a series of sand-prone channelised deposits within the Lista Formation (Fig. 1), or the underlying Maureen Formation, which comprises stacked lobe and channel deposits (Fig. 1). Provenance studies would confirm the parent sand from which injectites are sourced, however, here we argue for injectite-parent relationship. The mapped bowl structures presented here show a strong spatial affinity with the underlying Maureen Formation sands, with some bowls showing direct contacts at their base with the Maureen Formation sands (e.g. Bowl 8a; Fig. 2D). Additionally, the location of the mapped bowls overlie areas where there is a seismic pinchout or absence of the underlying Maureen Formation (Figs. 2A, 2C, 2D and 5). In cross section, the absence of Maureen Formation sands resembles channel incision (Fig. 5). One explanation for this pinchout is the presence of a mud-filled channel system. However, removal by a channel would mean a markedly different orientation (WSW-ENE and curving northwards) to all other channels along the same palaeoslope, which have a palaeoflow of west-to-east (Mudge, 2014). Furthermore, in plan view, the mapped pinchouts are not in a channel form. For example, Figure 2A shows the Maureen Formation pinchout narrowing in planform, whereas a channel would be expected to have a more consistent along-axis width. An alternative explanation is that the lack of Maureen Formation sands in this area is the result of depletion through the remobilisation and injection of sand into the overlying Lista Formation. The spatial relationship between the absence of Maureen Formation and the presence of overlying large bowl structures, the abrupt pinchout of the

Maureen Formation, and the connection with the overlying injectites, support this interpretation. The apparent absence of Maureen Fm. sand beneath the injectite bowls points to significant withdrawal from the parent sands, and the possibility that 'sand welds' formed. In diapiric systems, a salt or mud weld is a surface (or thin zone) that marks the complete, or near complete, movement of salt of mud (Jackson and Cramez, 1989). In a similar way, the complete withdrawal of sand and redistribution into an injectite network could result in a sand weld forming; and a welded surface that could separate concordant, but unconformable, strata. Once a sand weld forms beneath an injectite, it will cease to be supplied with new material, and injectite propagation will cease. In the case of the Maureen Fm., the resolution of the data does not permit us to confidently define whether a complete (remnant sand 0 m thick) or incomplete (remnant sand 0-50 m) weld developed (*sensu* Hudec and Jackson, 2011). However, the mapping of the Maureen Fm. (Fig. 2) does reveal development of a discontinuous sand weld (*sensu* Hudec and Jackson, 2011).

Origin of overpressure

Overpressure is a key factor required to generate clastic injectites (Jolly and Lonergan, 2002). For this North Sea case study, the overpressure is suggested to be generated from: i) depositional sands being encased in low permeability mudstones, and ii) influx of hydrocarbons into sandstone units (Ahmadi *et al*., 2003). Fluid pressures within the relatively shallow sandstones at the time of oil migration would have been near hydrostatic (Chiarelli and Richy, 1984; Barnard and Bastow, 1991 Kubala *et al.,* 2003). Fluid migration may not only have provided the source for overpressure, but potentially could have been the trigger mechanism needed for the initiation of clastic intrusion (e.g. Vigorito and Hurst, 2010; Monnier *et al*., 2014; Cobain *et al*., 2015, 2017). Other trigger mechanisms, such as seismicity, are also viable (e.g., see Cobain *et al*., 2017).

Timing of injectites

Hydrocarbon migration from the Beryl Embayment into the up-dip Palaeocene sands is constrained to between 55 and 65 Ma and is known to be post calcite cementation (Ahmadi *et al.*, 2003). Constraints on the timing of the process of injection are limited, however the maximum vertical height of a single intrusion structure is 152 m, indicating a minimum burial depth of at least this amount prior to intrusion. Although the sands within the Lower Lista Formation are relatively shallow compared to some injectite complexes, they have undergone some burial and compaction since remobilisation and deposition. The constraints on the timing of this process are limited and the values presented herein have not been decompacted. The measured vertical heights in features, therefore, represent a minimum burial depth (Huuse *et al.*, 2004; Parize *et al.*, 2007).

Scale invariance in injectite and the suitability of analogues

Sand(stone) injectites have been reported on scales ranging from millimetres in length and thickness (Goodall *et al*., 1999; Duranti *et al*., 2002; Hurst *et al*., 2011) to 10s metres thick and laterally extensive for kilometres (Huuse *et al*., 2004; Hurst *et al*., 2005, 2011; Hubbard *et al*., 2007; Cartwright, 2010; Cobain *et al*., 2017). For example, km-scale bowl-shaped injectites have been identified and described in a number of oilfields, including the Volund (Townsley *et al*, 2012; Schwab et al. 2015) and the Gamma Fields (Huuse *et al*, 2007). They can share morphological similarities in 2D, and commonly have a narrow grain-size range (Fig. 7) attributed to preferential fluidisation of very fine sand over other grainsize types (Cobain *et al*., 2015). The common occurrence of bowl shapes and fine grain size identified in injectites, along with scales ranging by orders of magnitude, suggests that injectites are scale invariant in their shape and composition; in other words injectite morphology and grain-size do not change when length scales are multiplied by a common factor. This characteristic could be critical in helping to predict and model sub-seismic scale injectite sands, and to identify appropriate analogues from higher resolution data that can offer the chance to better understand process and product relationships in injectite networks. However, why should injectites be scale invariant in their shape?

The scale invariance of sand(stone) injections in sedimentary basins is attributed to the host lithology being one of the main factors determining the geometry and architecture of an intrusion as it propagates (see Figure 2 of Cobain *et al*., 2015). In a similar way, faults and fractures are considered to be scale invariant (e.g. Scholz and Aviles, 1986; Schulz *et al*., 2010) as a function of the host lithology (e.g. Wibberley *et al*., 1999; Schultz *et al*., 2010). Furthermore, work has shown that the style of sand intrusions into fault zones varies as a function of lithology (Palladino *et al*., 2018). Previous research on intrusion dynamics has focussed primarily on igneous systems (McCaffrey and Petford, 1997; Thomson, 2007; Thomson and Schofield, 2008; Schofield *et al*., 2012a; Magee *et al*., 2015). However, similar geometries observed in both igneous and sedimentary intrusions suggest that emplacement mechanisms are comparable and controlled by the same external parameters (Cartwright *et al*., 2008; Polteau *et al*., 2008; Mourgues *et al*., 2012). It should be noted however, that although mechanisms of emplacement may be comparable, rates of emplacement are likely quite different between clastic injections and igneous intrusions (e.g., Ross *et al*., 2014; Sigmundsson *et al*., 2015). Properties of host lithology that affect intrusion morphology during emplacement include the propensity for brittle behaviour *versus* non-brittle (Schofield *et al*., 2012a), the homogeneity of the host strata (Jolly and Lonergan, 2002), and the principal stress orientation (Jolly and Lonergan, 2002; Rowe *et al*., 2002). As it is primarily the host lithology that controls final intrusion architecture, research and literature for scale invariance within igneous intrusions are utilised here.

Scale invariance over several orders of magnitude is recognised in igneous intrusions. One example is ‘broken bridges’, a distinctive morphology within igneous intrusions that has been well documented from centimetres up to several metres at outcrops (Nicholson and Pollard, 1985; Bussel, 1989). Schofield *et al*. (2012b) recognised that broken bridges developed between elongate magma lobes in the Faroe-Shetland Basin on a seismic scale of at least 10's of metres in height and with lateral extents of over several kilometres. Field data have also been used to test dimensional scaling and mechanical models, where a range of power-law scaling relationships for different types of intrusive structures can predict geometry for laccoliths and thickness-to-length relationships for mafic sills (Cruden and Bunger, 2010) implying scale invariance.

Experimental modelling also assumes scale invariance, where the use of dimensionless numbers demonstrates geometric and kinematic similarities between model and its natural prototype. This was first recognised by Hubbert (1937), and since then the principles of dimensional analysis of scaling have been used in many experiments replicating natural geological processes (Hubbert, 1951; Hubbert and Willis, 1957; Mourgues and Cobbold, 2003; Kavanagh *et al*., 2006; Rodrigues *et al*., 2009; Gressier *et al*., 2010). For clastic injectites specifically, Rodrigues *et al*. (2009) and Mourgues *et al*. (2012) both successfully recreated injectite geometries comparable to those in nature that can be up to several kilometres in size (Vigorito and Hurst, 2010), yet experimentally may only be several centimetres. These experiments support injectite morphologies being scale invariant where outside factors, such as host rock lithology, fluid pressure, and principle stress orientation, are at a scaled equivalent both geometrically and kinematically (Rodrigues *et al*., 2009; Mourgues *et al*., 2012).

The scale invariance of clastic injectites permits outcrop-scale data to be upscaled and applied to support seismic-scale interpretations. Therefore, the injectites at outcrop could be seismic forward modelled to aid recognition of injectites in reflection seismic data. Previously, the use of outcrop studies of injectites as analogues for subsurface examples has been limited to cases where the outcrop itself is of seismic scale (Surlyk and Noe-Nygaard, 2001; Vigorito *et al*., 2008; Scott *et al*., 2009, 2013; Vigorito and Hurst, 2010); an approach that limits the range of usable analogues and may ultimately mean inappropriate geometries used as analogues.

Implications for hydrocarbon exploration

Subsurface remobilisation and injection of sand has significant consequences on reservoir architecture, geometry, and porosity and permeability, which impact hydrocarbon recovery. In this North Sea case study, the procedure has been employed to provide unequivocal evidence for the origin of the sand bodies mapped in the Lower Lista Formation shale to be clastic injectites and not of primary deposition. Moreover, there is likely more complexity to those sand bodies than can be observed in the reflection seismic data. Therefore, a larger volume of sub-seismic injectites, and hence greater volume of sand and connectivity, is likely present than would be predicted from seismic data alone (Fig. 8).

As more exploration drilling in the North Sea is specifically targeting clastic injectite complexes (de Boer *et al*., 2007; Schwab *et al*., 2015), having the ability to map and interpret injected sandstones and predict their sub-seismic distribution accurately is crucial to achieve economic viability of drilling and production from such fields. Increasing our understanding of the architecture of clastic injectites will allow more accurate interpretation during exploration, and more informed placement of production wells, increasing the economic viability of reservoirs (Fig. 8).

Conclusions

The broadband seismic survey data from this North Sea case study, combined with nearby well logs, were used to map in detail the 3D geometries of clastic injectites over a sub-area of ~12 km^2. Fourteen bowl structures were identified, some of which showed a direct connection with the underlying Maureen Formation. Where this direct connection occurs, the Maureen Formation is partly absent, suggesting sand depletion as clastic material is forcibly injected upwards into the Lower Lista Formation forming the sand bodies mapped and interpreted as injectites, and that sand welds developed. This is a rare case where, in the subsurface, the parent unit can be confidently associated with clastic injectites. The impact of injectites on hydrocarbon reservoirs, as well as an increase in the industry targeting unconventional or complex reservoirs, means that the need for this knowledge and understanding has never been so pertinent.

The bowl-shaped morphology of the large seismically resolvable structures, and the common grain-size of similar geometries across several orders of magnitude suggest that clastic injectites can be viewed as scale invariant. This is a powerful implication as exhumed analogues need not be seismic-scale when other parameters such as geometry, tectonic setting and connection to the contemporaneous seabed differ from the subsurface systems. Rather a range of outcrop observations can be used to provide improved constraints on the sub-seismic injectite networks, and connectivity, to better predict and model fluid flow during hydrocarbon production, or carbon capture and sequestration.

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Table and figure captions

Table 1. *Quantitative analysis of 14 bowl structures*

2D reflection seismic profiles were taken at intervals of 50 m along both ILs and XLs for 14 bowl structures and the underlying Maureen Formation: plan view area (m^2), perimeter (m), XL transect length (m), IL transect length (m), depth of top Maureen Formation (IL) (m), top Maureen Formation to base bowl vertical distance (IL) (m),depth to base bowl (IL) (m), depth to top bowl (IL) (m), vertical depth of bowl (m), depth of top Maureen Formation (XL) (m), top Maureen Formation to base bowl vertical distance (XL) (m),depth to base bowl (XL) (m), depth to top bowl (XL) (m), vertical depth of bowl (m).

Fig. 1. (**A**) North Sea Basin showing present day distribution of Palaeocene-Lower Eocene sandstone in yellow (adapted from Mudge, 2014) and locations of large scale sandstone injectites in the Palaeogene of the Northern North Sea outlined in red (after Huuse *et al*., 2007). (**B**) Stratigraphy of the North Sea case study (adapted from Ahmadi *et al*., 2003).

Fig. 2. Example seismic sections through the study area. (**A**) Plan view of the study area showing extent of the Maureen Formation in pale grey. Black areas and the dashed line denote where Maureen is absent, and darker grey represents mapped sands within the Lista Formation. (**B**) Depth map in plan view of sands within the Lower Lista Formation and polygons outlining each mapped bowl feature. Yellow lines represent sections shown in Figure 2C-F. (**C-F**) Seismic cross-sections through mapped sands; yellow line is the top Maureen Formation pick, pink line picks base sand in Lower Lista Formation shale. (**C**) Section A-A'; steeply dipping, v-shaped bowl with complex internal sand architectures. (**D**) Section B-B'; v-shaped bowl where base of bowl is in contact with the top of the Maureen Formation. (**E**) Section C-C'; 5 km long section cutting through several outlined polygons (Fig. 2B). (**F**) Section through several bowl structures and well log A used to correlate sand bodies.

Fig. 3. Gamma Ray (GR) well log calibration to seismic interpretation, orange colour denotes low GR, primarily associated with higher sand content. (**A**) Profile through Bowl 5 (Fig. 2B),

where the underling Maureen Formation shows thick sand packages, overlying thin sand units interpreted as injectites. (**B**) Western edge of Bowl 5, where the Maureen Formation is picked out by high sand content, and the edge of the bowl shows multiple, thin sands interpreted as injectites. (**C**) Edge of Bowl 5, sand bodies appear to have pinched out. Some sand layers of unknown origin higher up in stratigraphy.

Fig. 4. Geometric properties and vertical position of the mapped sands. (**A**) Vertical depth to base of each bowl and depth from base of bowl to the top of the Maureen Formation. (**B**) Bowl height *versus* width, showing low to moderate degree of variability in height through bowls of different widths. **IL = inline, XL = cross line.**

Fig. 5. (**A)** Representative reflection seismic section taken through the case study area. (**B**) Simplified interpretation of depleted parent sand (Maureen Fm.) and resultant injected sand.

Fig. 6. Time steps of parent sand depleting as injectites form. (**A**) T1: pre-injection, fan sands remain unconsolidated and become overpressured as overlying shale deposited. (**B**) T2: parent sand starts to drain and deform as it injects into overlying strata. Overlying shale starts to deform in response to sand draining and injecting. (**C**) T3: injectites cease propagating with development of a sand 'weld', resulting in a large area of parent sand depleted and forming a "channel-like" cross-sectional shape.

Fig. 7. Photographs of clastic injectites of same grain-size (fine and medium grain sand) and geometry (dykes and sills) across a wide range of scales. (**A**) Photograph from a Palaeocene succession, North Sea. (**B**) and (**C**) Photographs from the Fort Brown Formation, South Africa. (D) Photograph from Miocene exposures in the Austral Basin, Tierra del Fuego, Patagonia, Argentina.

Fig. 8. (**A**) 3D reservoir modelling process for a single geological model (adapted from Bentley and Smith 2008). (**B**) Same model with sub-seismic injectites providing vertical connectivity between reservoir units.

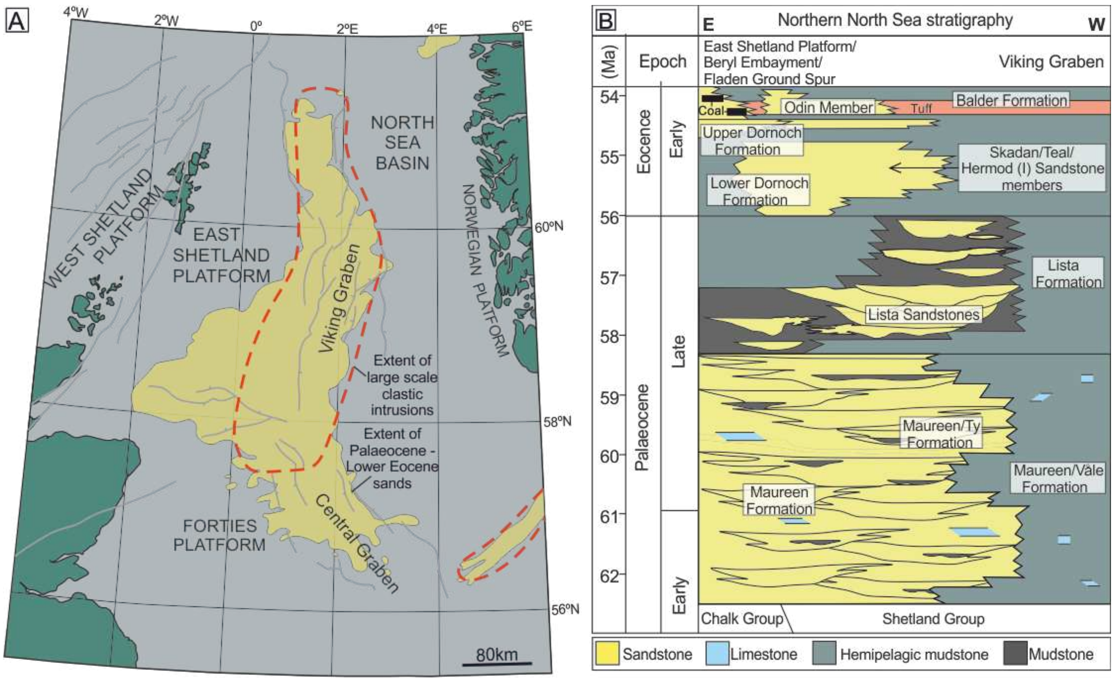

A
4°W
2°W
0°
2°E
4°E
6°E
60°N
58°N
56°N
NORTH SEA BASIN
WEST SHETLAND PLATFORM
EAST SHETLAND PLATFORM
NORWEGIAN PLATFORM
Viking Graben
Central Graben
FORTIES PLATFORM
Extent of large scale clastic intrusions
Extent of Palaeocene - Lower Eocene sands
80km
B
E
Northern North Sea stratigraphy
W
(Ma)
Epoch
East Shetland Platform/ Beryl Embayment/ Fladen Ground Spur
Viking Graben
54
55
56
57
58
59
60
61
62
Eocene
Early
Palaeocene
Late
Early
Coal
Odin Member
Tuff
Balder Formation
Upper Dornoch Formation
Lower Dornoch Formation
Skadan/Teal/ Hermod (I) Sandstone members
Lista Formation
Lista Sandstones
Maureen/Ty Formation
Maureen/Våle Formation
Maureen Formation
Chalk Group
Shetland Group
Sandstone
Limestone
Hemipelagic mudstone
Mudstone

Figure 1

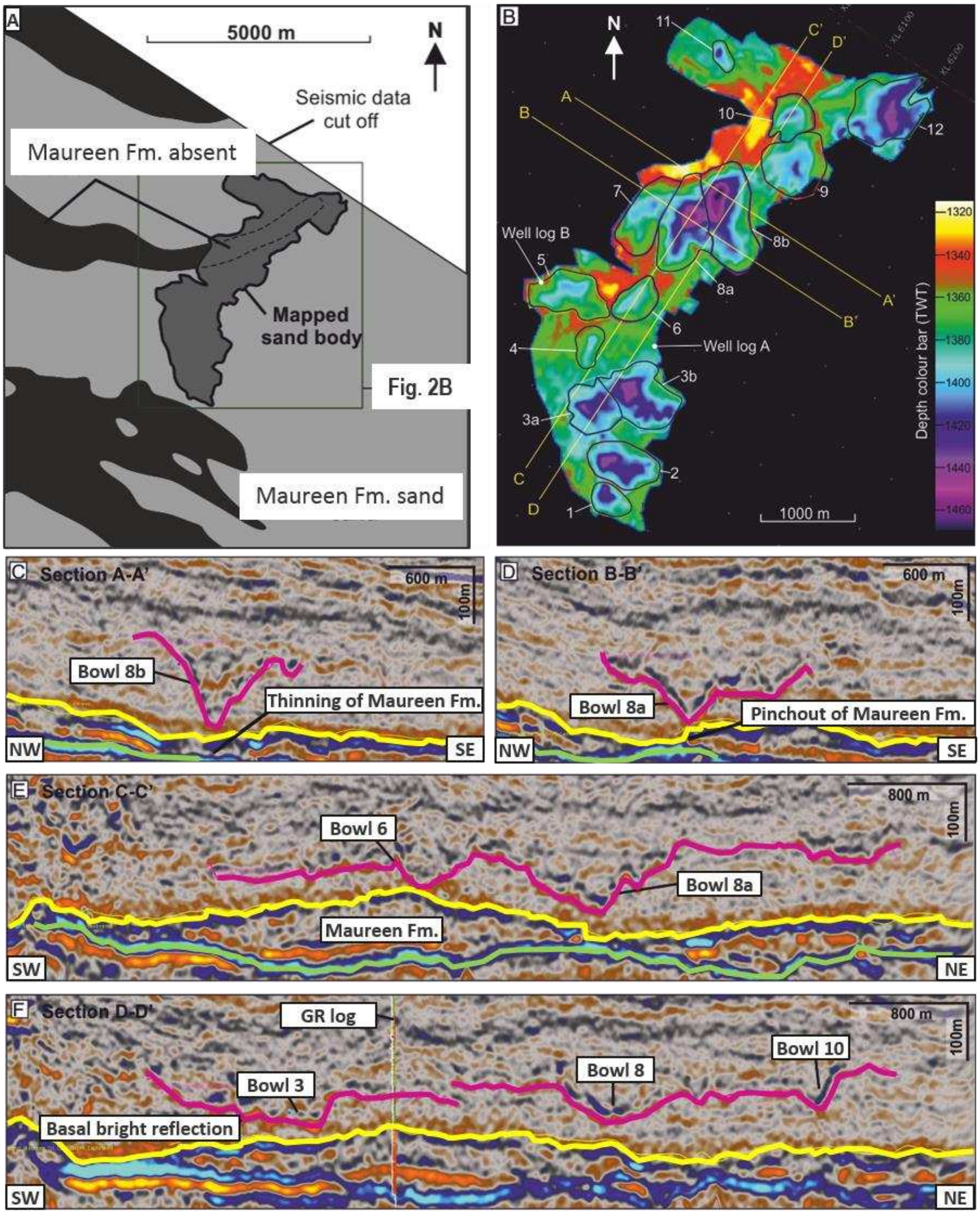
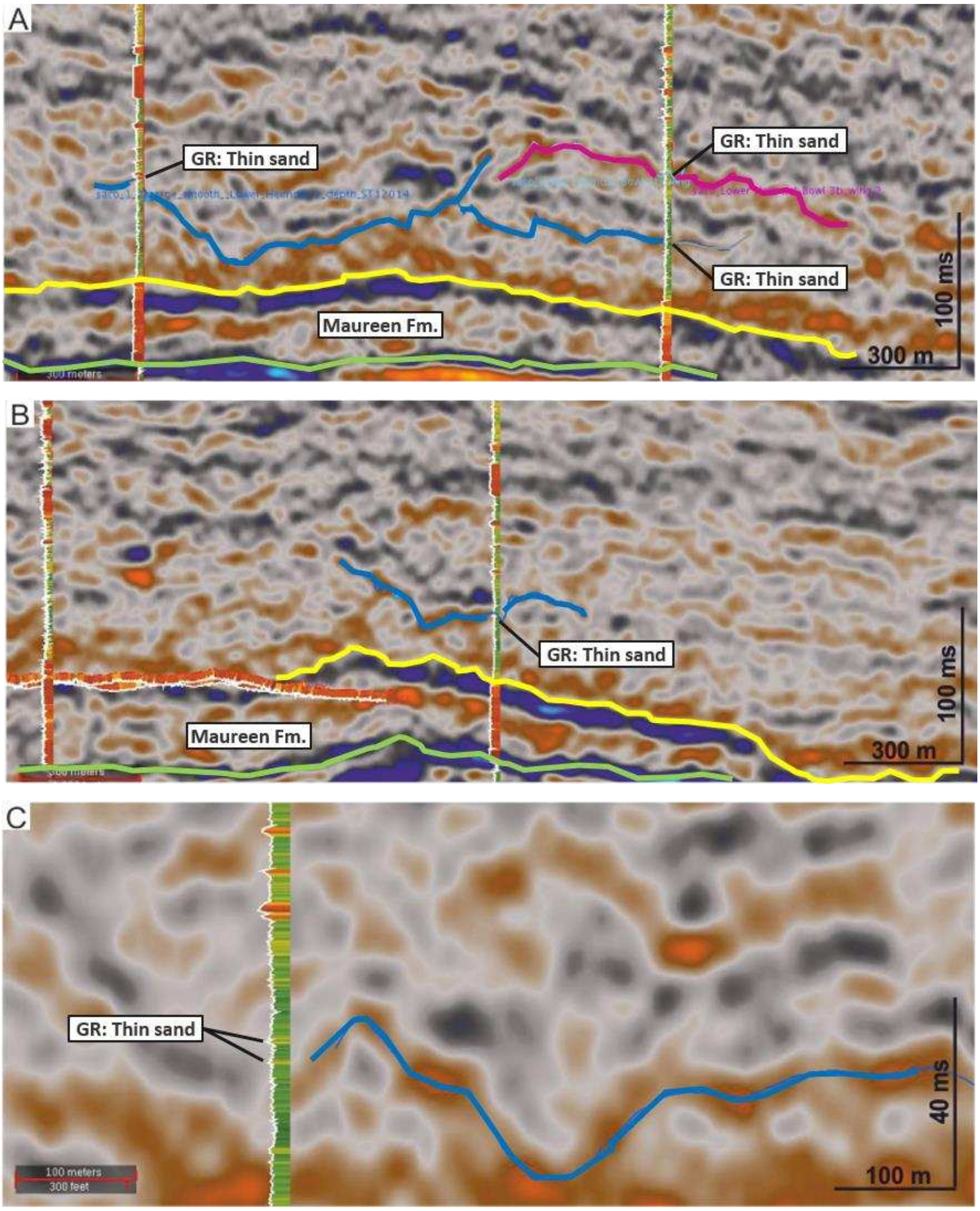

A
5000 m
N
Seismic data cut off
Maureen Fm. absent
Mapped sand body
Fig. 2B
Maureen Fm. sand
B
N
11
C'
D'
A
B
10
12
7
9
Well log B
5
8b
8a
A'
B'
6
4
Well log A
3b
3a
2
C
D
1
1000 m
Depth colour bar (TWT)
1320
1340
1360
1380
1400
1420
1440
1460
C Section A-A'
600 m
100m
Bowl 8b
Thinning of Maureen Fm.
NW
SE
D Section B-B'
600 m
100m
Bowl 8a
Pinchout of Maureen Fm.
NW
SE
E Section C-C'
800 m
100m
Bowl 6
Bowl 8a
Maureen Fm.
SW
NE
F Section D-D'
GR log
800 m
100m
Bowl 10
Bowl 8
Bowl 3
Basal bright reflection
SW
NE

Figure 2

556 

557 Figure 3

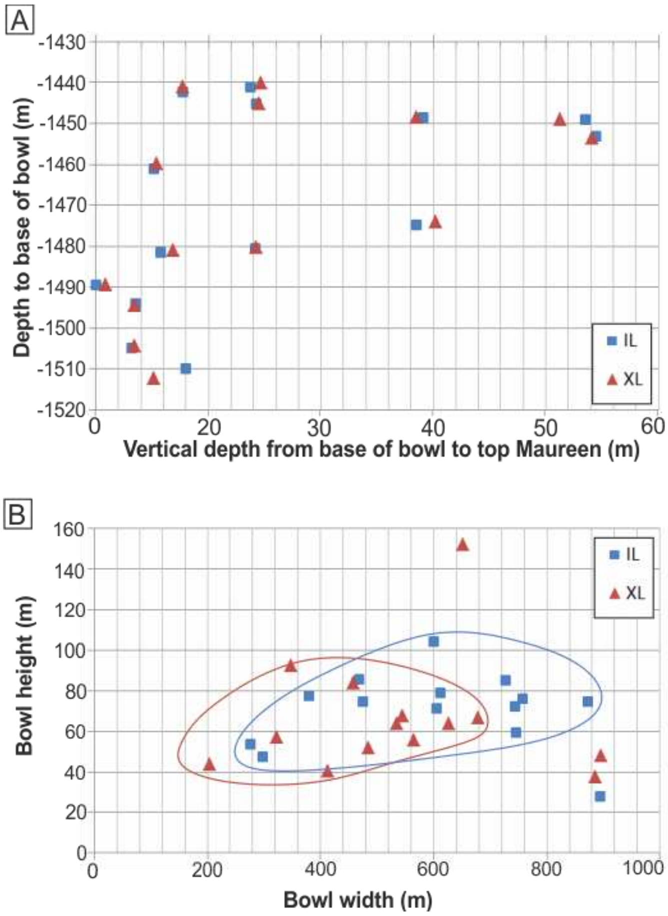


Figure 4

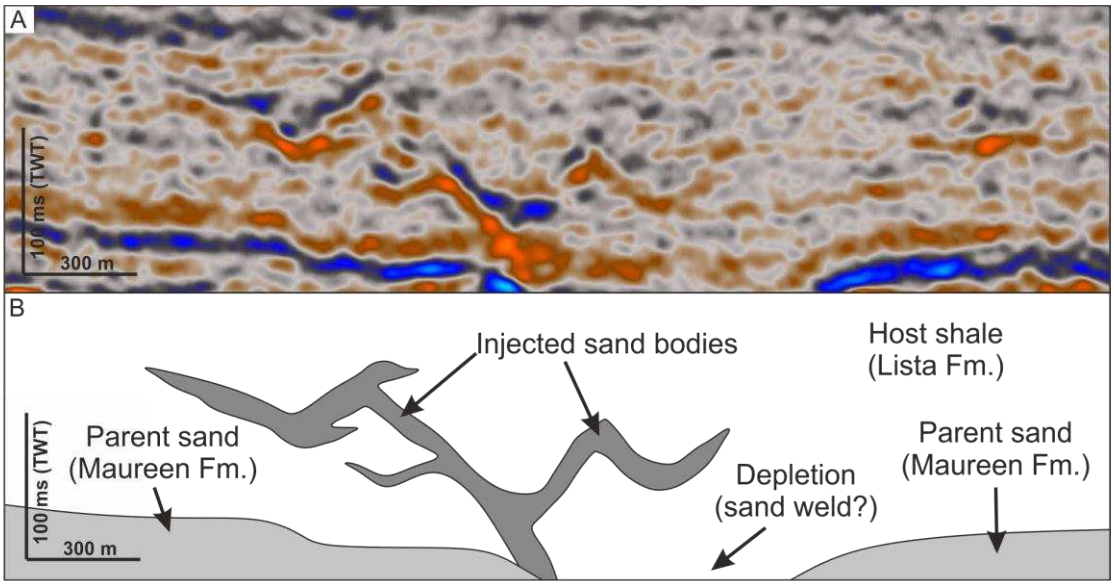


Figure 5

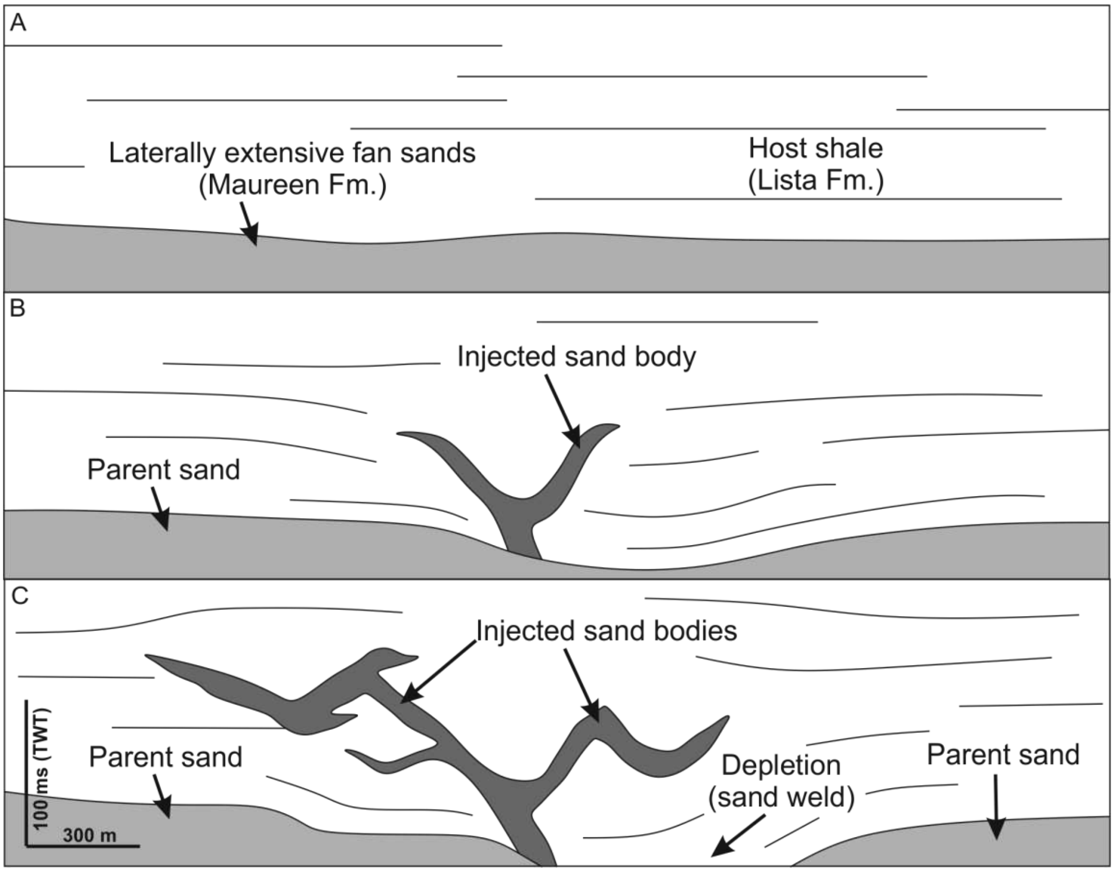


Figure 6

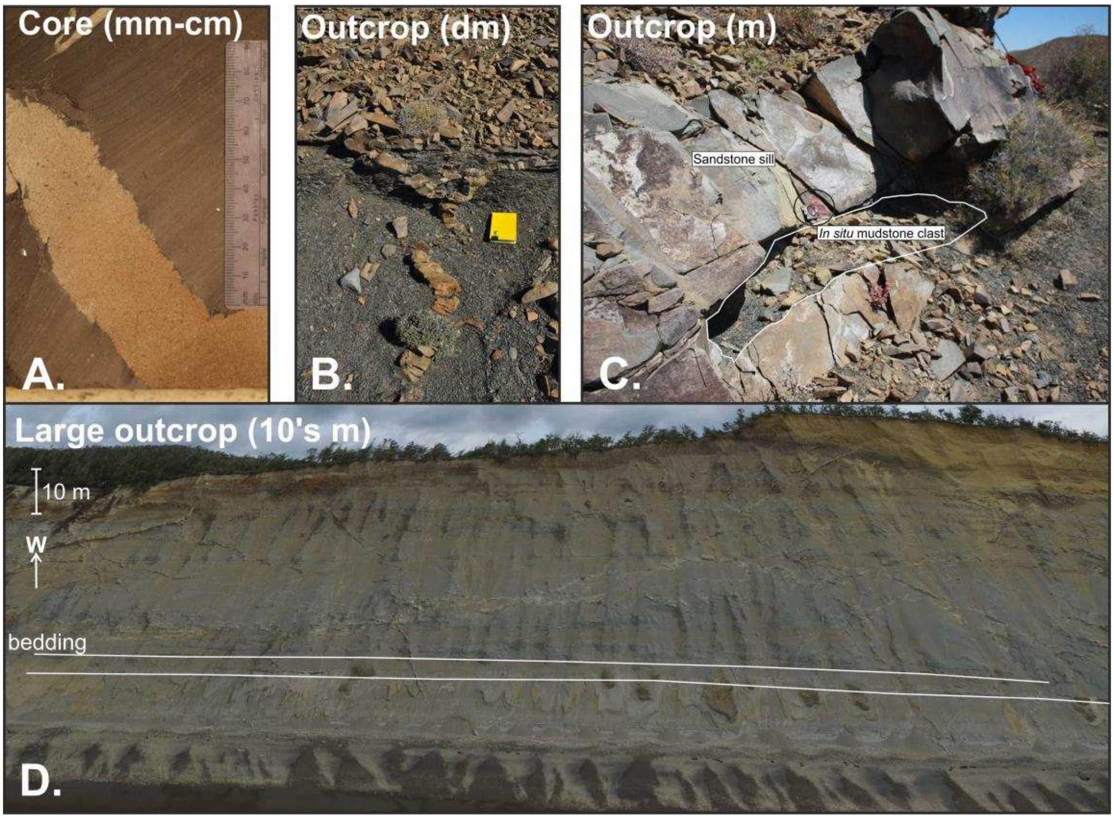
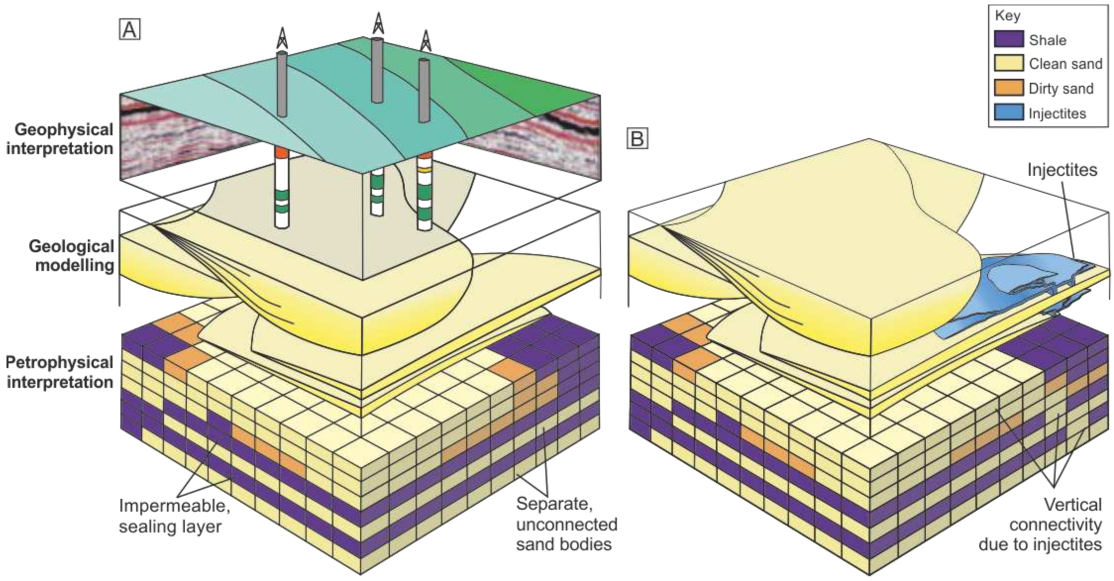


Figure 7



566

567 Figure 8