Subsurface Sand Remobilization and Injection: Implications for oil and gas exploration and development

22 – 23 March 2017

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Subsurface Sand Remobilization and Injection: implications for oil and gas exploration and development

22nd-23rd March 2017

The Petroleum Group
The Geological Society, Burlington House, London

Welcome to this two-day conference on Subsurface Sand Remobilization and Injection: implications for oil and gas exploration and development, organised by the Petroleum Group of the Geological Society. This booklet contains the programme and abstracts of all the talks and poster presentations. Information on the conference can also be found on the Petroleum Group Conference App, downloadable for free from all app stores.

The organising committee would like to thank the conference sponsors for their support of this event. The Petroleum Group and the Geological Society would not be able to continue to organise events of this scale without continued industry sponsorship.

Evidence of sand remobilization and injection as significant shallow crustal processes is increasingly common in outcrop and subsurface studies. Regionally-developed ‘giant’ sand injection complexes affect areas of 100’s to 1000’s km^2. Such complexeslocally harbour commercial volumes of hydrocarbons, act as fluid migration routes, compromise seals and record major periods of focused fluid flow, sometimes on a basin scale. The non-stratiform character of sandstone intrusions requires original solutions for the successful quantitative modelling, drilling and completion of wells and accentuates the need for a better understanding of these often enigmatic features. Sand injection and fluidization occurs on many scales from giant 1000s km^2 complexes to small-scale centimetricfeatures. This conference includes presentations on the characterization and interpretation of sandstone intrusions and associated facies, from grain to basin scale. Presentations on process and reservoir modelling and other practical applications are also given as we consolidate knowledge from improved subsurface imaging, exploration and development drilling and outcrop-based research and identify areas for future investigation.

Our thanks go to the Geological Society staff for their help and organisation, particularly Sarah Woodcock and Laura Griffiths for all of their hard work. The committee would like to take this opportunity to thank all contributors for their abstracts, presentations and posters. Finally, thank you to all conference attendees; we hope that you will find the conference interesting, have an opportunity to exchange ideas and learn something new.

Convenors:

Andrew Hurst (University of Aberdeen)
Simone Silcock (Statoil)
Hugh Dennis (Origo Exploration)
Mads Huuse (University of Manchester)
Cliff Lovelock (Shell)
John Wild (Independent)

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Oral Presentation Abstracts

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Wednesday 22nd March

Session One

Keynote: Sand Injectites in Petroleum Systems

Andrew Hurst[1], Mads Huuse[2]
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Development of several deep-water clastic reservoirs in the North Sea led to problems with well prognoses, geo-steering and often poorer or much better than expected well performance that, in many cases was associated with the presence of a range of scales of sand injectites. Investigation of 3D seismic revealed large-scale bedding-discordant sandstone geometry and core data showed sedimentary structures that were inconsistent with depositional processes. Sand injectites are now more commonly identified and described. Giant sand injection complexes are known to form geologically instantaneously as a result of very shallow pore-fluid overpressure causing regional hydraulic failure, sand fluidisation and its turbulent erosive flow into a propagating fracture system. Sand injection complexes have a tri-partite organisation of parent units, an intrusive complex and seafloor/surface extrusions. Within the intrusive complex a lower dyke zone, sill zone and upper dyke zone are present that with varying levels of representation are present in all injection complexes. 3D seismic data tend to image only the upper part of the sill zone in which km-scale saucer-shaped intrusions occur. Within the sill zone the architectural geometry of sandstone intrusions typically varies in response to a combination of variations in pore-fluid pressure and lithological heterogeneity. This records processes including: i) upward erosion by turbulent, fluidised sand, ii) exploitation of bedding weakness by intrusions, iii) modification of the hydraulic fracture network including brecciation, iv) bifurcation and narrowing of dyke aperture in response to permeability increases in host mudstone and v) grain segregation. The thickness and height of sandstone intrusions is always less than the thickness of the overburden.

Sandstone intrusions are remarkable reservoirs with cm-scale K_v often exceeding K_h and exceptional vertical and horizontal transmissibility; thin (sub-meter) pay zones can be exceptionally productive. In Tertiary North Sea reservoirs porosity averages ~30% and >Darcy permeability is common. Recovery factors are difficult to estimate because estimation of original in-place volumes is problematic; around 15 to >30% of reservoir volume cannot be resolved on seismic data. Oil columns are frequently >100m and in complete hydraulic continuity. Sandstone intrusions are essentially binary systems of sandstone and mudstone with reservoir characteristics frequently controlled by mixing the two end-member lithologies, for example mudstone-clast breccia. Gradation between sandstone and mudstone are untypical. Average grain size may decrease upward but the main control over poro-perm characteristics is the incorporation of fine-grained fragments from host strata and post-emplacement grain comminution rather than variations in grain size.

Diagnostic characteristics of sandstone intrusions include discordant relationships with bedding, erosive margins (particularly upper margins in sills, saucer-shaped intrusions and wings), jack-up of overlying strata, injection breccias (micro- and macro-scale), composite intrusions (layered fracture fills), associated mineralised fracture fills, a paucity of internal structures formed by hydraulic grain-segregation, micro-fractured sand grains and preferential abrasion of "soft" heavy minerals. Non-diagnostic features include pinch-out or tapering of intrusions as indicators of direction of intrusion and occurrence of structureless units. Acquiring micro-scale data to complement outcrop-scale data is an essential part of the verification of interpretations.

While knowing that pore-fluid overpressure is instrumental in the formation of sand injectites the origin of overpressure is poorly constrained. Because large-scale sand injection occurs in the very-shallow (< ~1.5 km burial) crust there are many sources of pore fluid that may contribute. Equally there are several often-cited mechanisms that may trigger the sudden onset of overpressure. In deep-water clastic systems a recurring characteristic is the presence of a large underlying or offset aquifer in which sandstone-prone units decrease in thickness and lateral extent upward (extensive lobes to isolated channels) thus focussing upward flow and amplifying the effect of pressure perturbations at depth that propagate into the shallower section. When intrusions reach the surface there is an instantaneous release of pore fluid pressure that will influence pressure gradients and fluid migration pathways throughout the basin.

NOTES:

Large-Scale Sandstone Remobilization and Injection in the Northern North Sea

Oluwatobi Olobayo[1,3], Mads Huuse[1], and Christopher Aiden-Lee Jackson[2]

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Soft-sediment remobilization, injection and fluid flow processes and their products such as sand injectites, mud volcanoes, pipes and pockmarks constitute a key, but under-appreciated component of sedimentary basins. Recent advances in subsurface imaging using high-resolution 3D seismic data, integrated with well data, geochemical data and outcrop data have greatly improved the understanding of these soft-sediment remobilization and fluid flow processes in sedimentary basins. The structures provide evidence of focused fluid pathways bypassing the stratigraphic and structural framework and thereby influencing sediment and fluid distributions in the subsurface. This paper presents substantial new results from the description, analysis and interpretation of large-scale sand injectites based on all available data from the Northern North Sea.

The studied intervals, which encompass the entire Cenozoic and Cretaceous succession, have undergone repeated, large-scale remobilization and injection of unconsolidated sand through time. The North Sea is the archetype Giant Injected Sand Province (GISP) with kilometre- scale sandstone intrusions observed within multiple stratigraphic intervals, but this is the first time the northern North Sea has been systematically studied on a regional scale. Well-documented, seismic-scale sandstone intrusions from the South Viking Graben, Outer Moray Firth, Faroe-Shetland Basin, Barent Sea and Norwegian-Danish Basin revealed emplacement during one or two episodes. However, the NNS show evidence for multiple (up to five) major episodes of emplacement. These sandstones, believed to be sourced from different stratigraphic levels, have intruded thick polygonally-faulted, diatomaceous and smectite-rich mudstones; probably facilitated by hydrocarbons and diagenetically-released water in spatio-temporally varying proportions.

These remobilized and injected sands thus have numerous implications for hydrocarbon exploration and production; and therefore be incorporated into present stratigraphic frameworks and reservoir models.

NOTES:

Triggering of sand remobilization: the importance on basin geometry

Christian Hermanrud[1] Iselin Tjorland Tjensvold[2], Lisa Marie Røynesland[2], Elisa Christensen[3], Maiken Haugvaldstad[4], Lillian Watsend[1]
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[3] *ConocoPhillips*
[4] *OMV*

Sand remobilization requires fast and therefore short-lived fluid flow. Such fast fluid flow requires a locally large overpressure gradient. If we can unravel the source of this overpressure gradient, we will have an improved chance of understanding how sand remobilization is triggered.

Fluid overpressures can have external sources (such as transfer of overpressured fluid from elsewhere), or internal sources (local grain rearrangement that reduces porosity and drives rapid fluid expulsion). Formerly proposed trigger mechanisms of the first kind include seal fracturing in underlying overpressured reservoirs and meteoric impacts, whereas the second kind includes earthquakes and underlying diapirism.

We have examined the geometry of several basins with known occurrences of sediment remobilization. Several of these apparently had fluid communication in continuous sands from (comparatively) deep basins to areas with shallow overburden, which is where the injectites were formed. In other basins, local triggers such as diapirs may have resulted in either excess fluid volumes of reduced available pore space, and thereby rapid fluid flow. Field exposures of injectites that are close to major fault planes suggest that the fluid flow in fault planes may result in a flow velocity that is sufficient for triggering of sediment remobilization. Leakage from overpressured reservoirs does not necessarily set up such rapid fluid flow, and leaked hydrocarbon structures are often not overlain by remobilized sediments.

Sediment remobilization has taken place in the North Sea basin during most of the Tertiary period as well as in the Quaternary. The basin flanks has been uplifted during this entire period, with sediment progradation towards the basin center and periods of creep and slumping at the basin flanks. While we do not have unique evidences that link these processes to the formation of sediment remobilization, both the locations within the basins and co-location with abrupt changes in sediment properties suggest that such processes have been more important that what has previously been suggested.

NOTES:

The value of outcrops in understanding the complexities in the subsurface injected reservoirs

Nicholas Satur, Asgeir Bang, Ivar Skjærpe and Sarah Alexandra Muehlboeck
Aker BP ASA

Sand injectites are a relatively new focus area in the oil industry and academia. It is an under explored play with only a handful of fields developed, and with a very limited number of outcrop examples, academic research is in its infancy when you compare it to other reservoir types.

Viewing outcrops of injected sandstones shows they are very complex and varied. There are details at different scales to be identify and understand that is be important to translate into subsurface datasets. Seismic and well data sees a small fraction of the complexities of sand injected reservoirs due to their limited resolution (seismic data) or areal sampling (well data).

A recent field course to Panoche Hills, California gave new insight into how the subsurface team on the Volund Field interpret the subsurface data. This new appreciation of the complexities on injected sandstones proved valuable going into a new drilling campaign on the field. Three important learnings were:

1. The outcrops show sections of the injected sandstones dykes can have a stepping form, creating a near vertical section of injected sandstones. Reflective seismic will not image these steps and often show as low amplitude “non-reservoir” on the Volund datasets. Examples from Panoche Hills show us this may not be true and we underestimate the net and connectivity in the reservoir.

2. There are a number of small (sub-seismic) aperture injectites in the background of the large seismically resolved injectites that can act as additional reservoirs. These may need to be considered during drilling operations as potential hazards or targets for production. Also these small injectites will often act as conduits connecting injected reservoir sands with the parent sandstones providing aquifer support.

3. Within the injected sandstones, there are mud breccia that on electronic logs show up mostly as mudstones and non-reservoir. Outcrops and cores from wells show there is often 50% sand matrix with good reservoir quality and thus should be defined as net reservoir. When mudstones are identified on the electronic logs within an area of a mapped injectite, we now question if we have penetrated a breccia and not exited the reservoir. This knowledge now has an impact on the geosteer decisions of the well, to continue on the planned trajectory or change the plan to search for the reservoir.

Even in these economic constraint times, there has been great value for the Volund team to study the outcrops of injected sandstones, more accurately interpreting net reservoir, having a better understanding of the chance of aquifer support in individual injectites and making the making more correct decisions during drilling operations to stay within the reservoir. The added knowledge form the outcrops will ultimately allow the team to maximise the reserves from the field and identify new targets for exploration.

NOTES:

A Sand Injectite Stratigraphy for the South Viking Graben, Outer Moray Firth and Central North Sea: Implications for Oil and Gas Exploration and Development

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The exploration of oil and gas in the North Sea since the late 1960s have conducted the North Sea Basin to be among the most data rich and well understood basins on Earth. It is estimated that over 500 000 person-years (companies, research institute, universities and government agencies) of effort has been expended on data acquisition and interpretation in an attempt to understand the geology of the North Sea (NS). However, the NS still contains many poorly understood structures and deposits. One of the most intriguing and economically important successions is the Cenozoic overburden to the North Sea rift, comprising numerous oilfields hosted within sandstone intrusion or depositional sandstones that are modified by sand remobilization and injection that contain hundreds to thousands of km^3 of sand showing geometries similar to igneous intrusions or hybrid depositional-intrusive geometries. The occurrence of sandstone intrusions in the North Sea has been known for decades and their significance is steadily gaining recognition among North Sea explorers who recognize the reservoir and trap potential and migration path/leakage path significance associated with giant sand injection complexes. Meanwhile, researchers are striving to uncover the underlying mechanisms leading to repeated and basin-wide remobilization of such large quantities of sand.

Seismic-scale sandstone intrusions can be subdivided into those that are visibly attached to their parent sandstone and those that are detached. In all cases, seismically imaged sandstone intrusions form inclined sheets or cones, typically at 15-45 degrees relative to their host strata and usually between 100-300 m in height, while dykes that are steeper to bedding are also present, as seen in core, but not imaged by conventional 3D seismic data. Sand remobilization processes may result in both sand and host rock being injected into the overburden resulting in inverted stratigraphy detectable using standard stratigraphic methods.

This study presents stratigraphy, distribution and geometrical characteristics of occurrences of sandstone intrusions in the Cenozoic of the South Viking Graben, Outer Moray Firth and Central North Sea. Key intrusive episodes include the early Eocene, middle Eocene, late Eocene, and mid/late Miocene (Huuse et al. 2007; Huuse 2008) (Fig.1), whilst late Cretaceous, Paleocene and Oligocene episodes are important locally (Jackson et al. 2011; Dmitrieva et al. 2012; Andresen & Clausen 2014), including in major oil fields such as Mariner and Grane. Each of the key intrusive episodes quoted above revealed injected sand volumes the range of 10 to 100 km^3. Knowing that the grain concentration within the fluidized sand-fluid mixtures is in the range of 0.1 to 0.3, it implies that the fluid volumes expelled at basin scale during each intrusive episode is in the order of thousand km^3, highlighting that sandstone intrusions are a major component of basin-scale fluid migration and dewatering structures.

Studying geographic extent of each sandstone intrusions event, we aim to better constrain mechanisms responsible of their emplacement. Mechanisms governing sand injection can be subdivided into geological setting, primers and triggers. These mechanisms have been debated for many years and vary from place to place. In this study, we show that within a single intrusive episode, emplacement mechanisms might differ at basin scale. In the North Sea, we also observe that youngest sandstone intrusion episodes migrate towards the East of the basin. Displacement of their distributions towards the East likely reflects the progradation of sediments, depocentres also towards the East within the North Sea likely due to the erosion of the Scottish reliefs and the drainage and progradation of clastic sediments in the North Sea.

Recently, improved models for Cenozoic deposition and remobilization of sand poses challenges to prevailing sequence stratigraphic models and provide an opportunity to revise exploration strategies for Cenozoic targets. In the northernmost North Sea, for example, the scale of sand remobilization is so extensive that even the lowermost Cenozoic is frequently connected to the Pleistocene (Olobayo 2015). Seal and trap integrity is thus suggested to be the main cause of the numerous dry exploration wells targeting Paleocene sands in this reservoir rich province.

To conclude, detailed analysis of each intrusion event have shown that the Balder Fm., is dominated by major mass transport deposits which have been heavily remobilized after < 0.5 km burial, outlining 'jig saw'-like domal sandstone blocks with differential compaction domes and sand injectite carapaces (formerly 'giant pockmarks')and have been secondly remobilized by sandstone intrusions. Middle Eocene 'Martini-glass' shaped injectites are very widespread, they form prospects, migration paths and drilling hazards. These are thought to be fully injected. Late Eocene/Early Oligocene injectites form channel margin wings around Alba Field (Grid Fm) - is Alba really the only major oil field at this level?

Oligocene and Miocene injectites have been previously under-appreciated, they are in fact very widespread from Moray Firth to the Atlantic margin, including fully intruded and attached injectites, likely feeding extrudites in Utisra Fm. The Spatio-temporal sandstone recognition step is essential for unlocking remaining Cenozoic prospectivity.

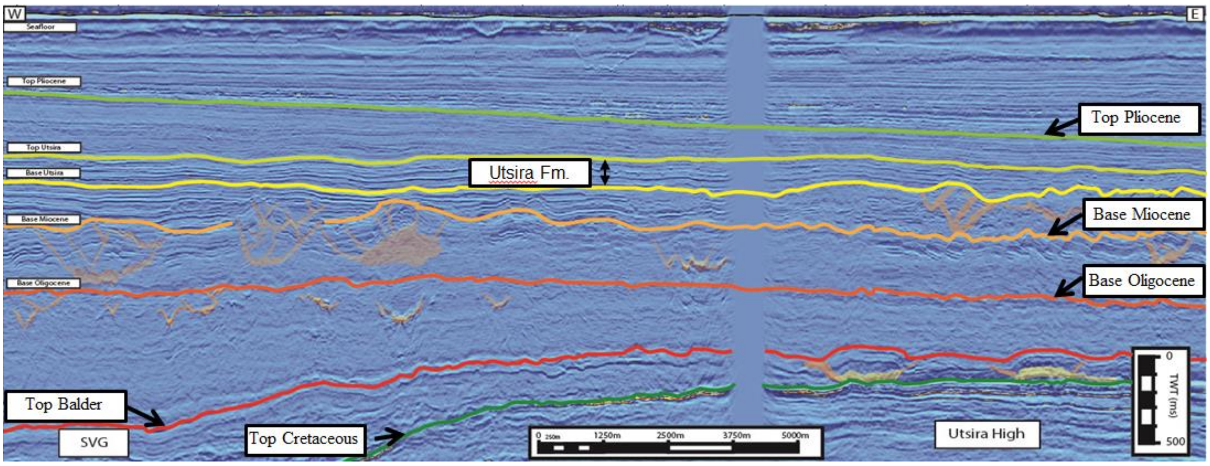

Figure 1: W-E trending seismic line across the South Viking Graben and the Utsira High showing stratigraphy from top Cretaceous to seafloor. Discordant amplitude anomalies are highlighted in orange and are interpreted as sandstone intrusions. Note the occurrence in this study area of at least four intrusions events. From base to top: 1) sandstone injections departing from turbiditic channels (Grane field), in details, discordant margins crosscut Top Lista Fm. suggesting a Late Paleocene/Early Eocene event. 2) Conical intrusions hosted in the late Eocene and deforming the Base Oligocene (Late Eocene/Early Oligocene event). 3) Irregular saucer-shaped intrusions with complicated intrusions complexes crosscutting most of the Oligocene succession and terminating against the base Miocene. The second intrusion (from the left) affects Miocene deposits suggesting possibly two phases of injections. In 3D, jack-up created by intrusions on the Early Miocene display sinusoidal organization leading us to believe that this intrusion complex is probably sourced from Oligocene channels (Skade Sst). 4) Conical to saucer-shaped anomalies crosscutting Early Miocene deposits and uplifting the Base Utsira (Mid-Miocene Event).

Acknowledgements

We are grateful for the support of the sponsors of Sand Injection Research Group Consortium Phases 1 & 3.
PGS kindly provided access to their MegaSurvey for sand injecton research, including the PhD of TO at the University of Manchester.
PGS and TGS kindly provided access to their dual-sensor broadband 3D seismic data from the South Viking Graben from which most of the images on this poster are derived.
Schlumberger generously provided Petrel seismic interpretation software for the University of Manchester.

NOTES:

Reconstruction of Subsurface Sand Mobilization from Seismic Data

Andreas Laake
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Sand mobilization often occurs in deltaic depositional environments as a result of sediment load and dewatering during sediment compaction. Three dimensional seismic data from the Central North Sea are used to illustrate how color-processing allows the reconstruction of the depositional environment and mobilization of the sand. We found that the shape and thickness of the resulting sand injectite structures is correlated with the distance from the source channel (Figure 1).

Sand injectites can be delineated and extracted from seismic prestack depth migration data using the structural attribute from the structurally sharpened continuous-colour red green blue (RGB) process. Multimeasurement streamer acquisition and processing, coupled with isometrical data sampling enabled the detecting complex sand injectites because of the uniform and unbiased sampling in vertical and lateral directions. Combining seismic sections and horizons textured with seismic attributes in a chair diagram rendering provides a useful approach for geological interpretation in 3D. Texturing seismic horizons with structurally sharpened red-green-blue (SRGB) colours enables the interpreter to recognize morphological patterns that can reveal clues for the interpretation of depositional and erosional environments.

The shape and thickness of the sand injectites is determined by the pressure after deposition of the sands. In the shallow part of the prograding delta, chaotic injectite geobodies are observed. Near the shelf break, large, round bowl-shaped injectites indicate that the pressure release largely occurred in a crater-like shape. With increasing distance from the shelf break the pressure sediment load and, thus, the pressure increases. Thin and extensive sheet-like injectite structures develop along the fault (Figure 2).

Correct mapping of sand injectites and their correlation with the fault network can be used to map drilling hazards where the sands are still not consolidated. Consolidated sand injectites may be important pathways for fluid migration across seals in sandstone reservoirs that have frequent shale seals. And finally, the shape of sand injectites may provide clues for their location in the deltaic depositional environment and the pressure regime during and after deposition.

The author thanks BP and Schlumberger for the permission to publish the data.

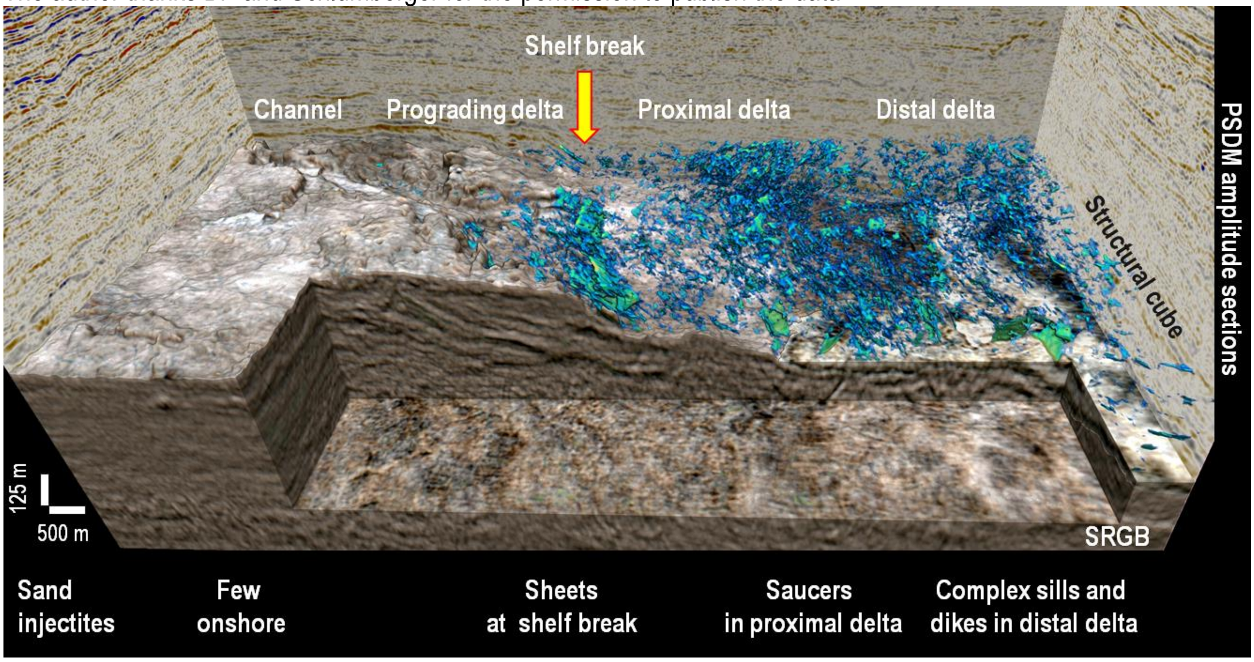

Figure1 : Correlation of sand injectite structures with the distance from the sand source.

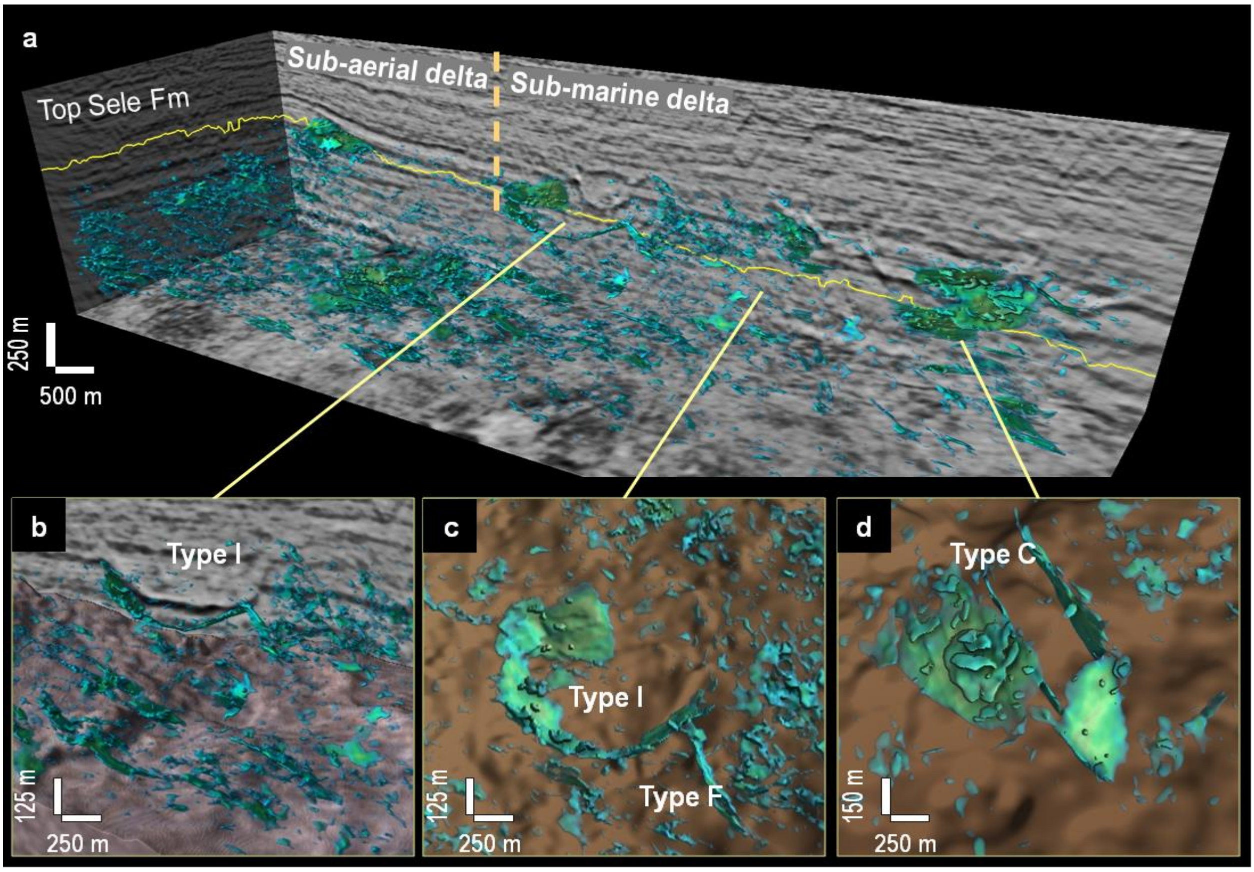

Figure 2: Sand injectite features and their correlation with the deltaic depositional environment, overview of the structural cube in the context with PSDM amplitude sections (a), zoom into selected sand injectite features Type I (b), Types I and F (c), Type C (d).

NOTES:

On the origin of some large-scale sand injections

John Wild

Large-scale sandstone remobilisation is commonly interpreted to occur through the rapid fluidisation of a large body of sediment causing the upward and lateral injection of sand into hydraulic fractures. An additional model based on seismic, core, outcrop and production data will be presented in which a longer term grain-flow process occurs when an over-pressured trap is breached and sand is entrained by the liberated fluids to be redeposited higher in the overburden.

Wild & Briedis (2010) showed the relationship between mounded, stratigraphically isolated sands and the presence of rafts of chalk above corresponding ‘pock marks’ in the underlying chalk surface, separated by stratigraphically anomalous sand. This geometry requires both overpressure to elevate the chalk rafts and re-mobilised sand to prop them up, but the underlying geology is not favourable to invoking the established model.

This paper proposes that in some cases the breaching of an over-pressured trap may create conditions favourable to sand piping, a phenomenon of concern in monitoring of dam stability and light hydrocarbon production and actively induced in some heavy oil production. The deposition of the entrained sand may account for the observation of sedimentary fabrics observed in outcropping sills. This process implies longer time-frame of sand injection than the established models of injected sands.

NOTES:

A giant sand injection complex in stacked turbiditic channel sandstone: a case study of the Eocene Tumey Giant Injection Complex

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Sandstone intrusions in the Tumey Giant Injection Complex (TGIC) occur entirely within the mid-late Eocene Kreyenhagen Shale Formation, a regionally developed unit that comprises interbedded mudstone and sandstone. In the study area, the Kreynhagen Shale outcrop is an oblique section of a large channel complex that contains stacked turbidite channels overlain by a mudstone, which has an upper 50 m thick diatomaceous unit.

All depositional sandstones display evidence of sand fluidization and remobilization and pristine depositional structures are uncommon. Fluid escape structures are commonplace but, despite homogenisation of internal depositional structures, normal or reverse gradation is sometimes preserved. Mudstone overlying the sandstone channels displays evidence of erosion caused by the fluidised sand flow. Angular mudstone clasts are frequently preserved at the top of these channels. An extensive network of sandstone intrusions interconnect pervasively with depositional sandstone.

Seismic-scale saucer-shaped and wing-like sandstone intrusions typify the large intrusive units. Two end-member geometries are identified for saucer-shaped intrusions. i) The main sandstone body is “detached” from the parent unit but connected by an intense network of dykes and sills. Intrusions have a meter-scale bedding parallel central body (inner sill) that are several hundreds of meters wide. Approximately symmetrical wings cross the stratigraphy at high angles and transform into thin ‘outer sills’ at a similar stratigraphic level. ii) Saucer-shaped intrusions are directly connected to the parent unit with a common point of origin from which they step up and diverge through the stratigraphy. Both the inner and outer sill segments are not always present. Field observations indicate that the two types of geometry may be related sections of the same saucer-shaped sandstone intrusion.

Seismic-scale wing-like geometries occur that are very similar to geometries imaged in the sub-surface. An approximately 500m long wing-like intrusion emanates from a 45 m thick sandstone-filled turbidite channel. Its maximum thickness is ~30 m and it steps up through the stratigraphy for more than 200 m. The margins of the intrusion are characterized by an injection breccia that at the base of the wing may be 10’s m thick.

The top of the TGIC is truncated by a regionally-developed unconformity that down-cut into an intensely hydro-fractured and sand-intruded diatomaceous interval, which is typified by injection breccia that varies in thickness up to ~50m thick. We believe that the injection breccia was generated when dykes propagating through the underlying strata reached the low density, fluid-rich diatomaceous muds and caused an instantaneous increase in pore-fluid pressure that triggered pervasive hydraulic failure.

Abundance of depositional sandstone and the associated sandstone intrusions in the TGIC differentiate it from other outcrop of giant injection complexes, as does the pervasive, thick injection breccia in diatomaceous mudstone in the shallow section. Thus the TGIC is an important new outcrop analogue for sub-surface modelling.

NOTES:

Wednesday 22nd March

Session Two

Sandstone intrusions along faults: a new element in fault seal analysis of multi-layered siliciclastic reservoirs

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The knowledge of fault zone structure has an enormous impact on predicting fluid flow behaviour and distribution of hydrocarbons in a reservoir. In fact, faults produce a series of fault rocks that influence the flow properties and sealing capacities. In reservoirs comprising rocks of either low porosity/permeability or high porosity/low permeability (i.e. carbonates), faults may provide a significant connectivity and are considered the most efficient pathways for fluid migration. In multi-layered siliciclastic reservoirs, where connectivity is typically enhanced by the geometry and distribution of high- porosity/permeability lithologies such as sands, faults can result in a general reduction of the fluid flow transmissibility. This is mainly due to a number of factors including the juxtaposition of permeable and impermeable rocks, clay smearing produced during fault movement, the creation of fine-grained cataclasites along the fault zone and, diagenetic processes leading to the closure of pores.

Traditional fault seal analysis techniques such as the Shale Gouge Ratio (SGR), the Clay Smear Potential (CSP) or the Shale Smear Factor (SSF) are algorithms developed to predict the percentage of clay contained in a fault zone which cuts through multi-layered siliciclastic reservoir rocks and hence to assess its sealing potential. Although these techniques are generally applicable to rock sequences which consist of well-cemented sands and plastic clays/shales, they are not well suited for lithologies comprising poorly consolidated or unconsolided sands. In fact, in this latter case, fault activity may lead to a transfer of sand from the faulted blocks into the fault zone, thereby significantly varying the porosity and permeability characteristics along the structure.

Sand can be incorporated along the fault planes due to: i) sand beds being sheared resulting in deformed ribbons parallel to the fault plane; ii) sand beds being dragged and rotated until they become parallel to the fault plane; iii) fluidized sand being directly injected along the fault zone (Lewis *et al.*, 2002).

In central California numerous examples of sands filling both extensional and contractional faults have been observed affecting Meso-Cenozoic sandstone/shale successions (Palladino *et al*., 2016) (Fig. 1).

In the Panoche and Tumey hills area both contractional and extensional faults, containing sandstone intrusions, frequently cut through the Moreno Formation (Late Cretaceous-Early Paleocene) and the Kreyenhagen Shale (Middle-Late Eocene) (Vigorito *et al*., 2010). These sand-filled structures represent a later episode of sand remobilization which postdates the intrusion of the Panoche Giant Injection Complex and the Tumey Injection Complex.

In the Santa Cruz area extensional faults containing hydrocarbon-filled (residual oil and bitumen) sandstones have locally been observed within the organic-rich biosiliceous deposits pertaining to Santa Cruz Mudstone (Late Miocene). Based on cross-cutting relationships it is found that these structures clearly postdate the Yellowbank Creek Injection Complex (Scott *et al*. 2009).

In both the considered areas, the recognized faulting events were are able to remobilize just a small amount of sands compared with the huge sand budget involved during the emplacement of the earlier giant injection complexes. The influence of these structures on multi-layered siliciclastic reservoirs is twofold: firstly, sandstone-filled faults can increase the connectivity, acting as conduits for hydrocarbon migration, particularly in sequences dominated by mudstones In fact, sand-filled structures can connect sand-rich units (reservoir rocks) in different stratigraphic intervals which are separated by thick mudstone intervals. In addition, the movement of the sand can produce an abrasive effect which has the potential to “clean” fault walls smeared with clay-rich fault gouge;

Secondly, sandstone-filled faults cutting through a top seal reservoir can connect the reservoir with either the topographic surface or sea bed resulting in hydrocarbon leakage. We believe that the understanding of sandstone-filled faults is fundamental for fault seal analysis and implementation of 3D reservoir models to multi-layered siliciclastic reservoirs. Central California offers excellent field outcrops to use as analogues for subsurface reservoirs. The consideration of sandstone-filled faults could greatly help the recovery of oil from newly discovered or mature reservoirs as, for example, in the case of numerous sand-injection prone reservoirs recognized in the North Sea.

Fig. 1 - Examples of sandstone-filled extensional faults (left) and contractional faults (right-side) recognized in Central California

NOTES:

Open versus closed injectite systems: implications for injectite deposits and processes

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Injectites are known to show a very wide range of sedimentary facies, varying from complex poorly sorted mixtures with giant clasts, and evidence for large-scale erosion on their flanks, through to homogenous deposits with no evidence for erosion at their margins. These variations have led to much debate on the nature of their formative flow processes. Here, we contend that at first order many of these variations are related to the overall nature of the injectite system, and in particular whether systems are open – reaching the sediment surface – or closed – where there is no connection to the surface.

Some outcrop analogues enable the nature of the injectite system to be ascertained, because they show the presence of extrudites, thus showing an open system with a clear connection to the surface. In contrast others, such as some of the deep-marine fan units in the Karoo Basin, South Africa, show patterns on fracture surfaces on the edges of injectites suggesting that the injectites formed at considerable depth. Furthermore, many of these are associated with downward orientated injectites and thus the injectites terminate in a closed system with no connection to the surface. Comparison of the features within these different systems reveals some striking differences. Open systems are associated with large clasts, poor sorting, highly variable sedimentary facies, and a range of erosional features on the margins of the injectites (Fig. 1A). Closed systems instead show more homogeneous deposits with better sorting and less mixing of clasts. Notably in the Karoo, transported mud clasts are found at both the top and base of sills (Fig. 1B) suggesting that the flow was highly concentrated, because the particles at the top were unable to settle through the sediment; similar features are also observed in other examples. The preservation of delicate structures such as the pristine plumose structures on the fracture surfaces of injectite margins also indicates that significant abrasion did not take place during injection emplacement. The absence of any evidence of abrasion or erosion further suggests that the injections were associated with high-concentration, relatively slow-moving flows. Figure 1 summarises these sedimentary observations and a proposed range of other differences between open and closed systems.

So why are there such prominent differences between open and closed systems? Here we propose that when fractures occur at depth without an open connection to the surface, then there is a limited capacity for flow dilution, with liquid and particulate components moving together from high to low pressure, thereby encouraging high-concentration flows. Such high-concentration flows are far less likely to exhibit highly turbulent conditions because flow viscosity varies strongly (by orders of magnitude) with flow concentration. As a consequence, the viscous term in the Reynolds equation is likely dominant unless the cross-sectional dimensions (fracture aperture) of injectites become large. Furthermore, at concentrations that may be close to the packing limit, there is limited ability for flows to mix sediments, and velocities may not be sufficient to move very large clasts. In contrast, once connection to the surface occurs, a greater fraction of carrier fluid to particles can be accommodated, enabling highly turbulent and lower-concentration flows to form. Essentially, overpressured water is able to escape to the surface, and in so doing, carry particles with it. Observations of active sand volcanoes in nature and in the laboratory demonstrate that the resulting extrusions are not high-concentration granular flows, but are lower-concentration systems. A connection to the surface also encourages a much greater pressure differential to occur in contrast to closed systems, and in turn higher velocities of the upward moving carrier fluid, thus enhancing the ability to transport large clasts.

Increasing our understanding of the flow processes and resultant internal facies of clastic injectites increases the predictability for them acting as fluid flow pathways in the subsurface, allowing for more accurate interpretation and modelling during exploration.

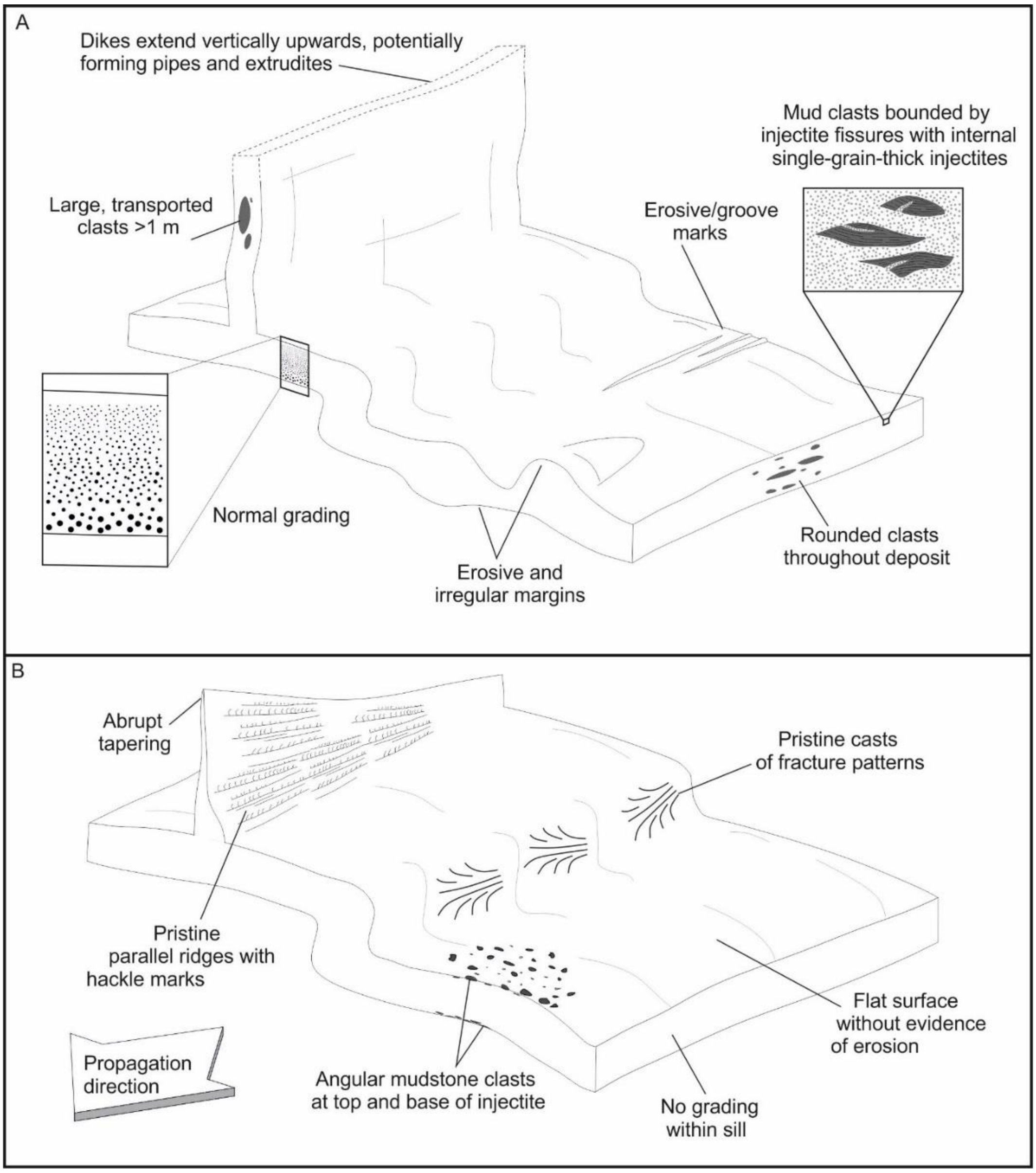

Figure 1. Recognition criteria for open and closed clastic injectite systems. (A) Injectite architecture and features expected as a product of highly turbulent flow in open injectite systems during clastic injection. Such systems can show transport of large clasts, poor sorting, and highly complex and spatially variable internal facies. Grading, both normal and reversed, within injectites is typically related to turbulent flow and is most likely a function of parent sand composition and preferential fluidisation of grain sizes. Erosive or groove marks on the margins of sills or dikes and rounded clasts throughout the deposit also suggest turbulent flow. (B) Schematic diagram of typical architecture and structures associated with injectites in closed systems, dominated by high-concentration flows with low Reynolds numbers. Flows show dramatic segregation of particles, and lack the extreme spatial variability of open injectite systems. The margins of such systems may also show a range of patterns on fracture surfaces, indicative of being formed at considerable depth. Adapted from Cobain et al. (2015; GSA Bulletin, 127, 1816-1830).

NOTES:

From parent units to a palaeo-seafloor: the anatomy of the Panoche Giant Injection Complex

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The Panoche Giant Injection Complex (PGIC) may be the most extensive and best exposed complex of sandstone intrusions covering an area between 300 and 400 km². In arguably unique exposure, spatial and genetic relationships are visible between sandstone intrusions, depositional parent units, hydraulic fracture systems and a palaeo-seafloor. Up to 1200 m of stratigraphic section are cut by the injection complex. A major turbidite channel (Dosados Sandstone) running ~NW-SE constitutes the parent unit for the injected sand. Several deeper and larger sandstones contributed to the aquifer that controlled pore-fluid pressure and fluidised the Dosados Sandstone. Within the host strata, sandstone intrusions form a well-defined tripartite organisation in which a lower dyke zone (LDZ), a sill zone and an upper dyke zone (UDZ) are present. Dykes in LDZ connect parent units to the overlying sill zone, the base of which is typically a few tens of meters above the top of the shallowest parent units and is the depth at which a lithostatic equilibrium surface existed when injection occurred. Sills, fed by underlying dykes, have an overall saucer-shaped geometry and step upward in the stratigraphy where they inter-connect with dykes, other sills and occasionally with depositional sandstones. In the UDZ, dykes often cross the entire stratigraphic interval between the sill zone and the palaeo-seafloor where some dykes feed sand extrudites. Sandstone intrusions differ in both size and geometry, varying in length from a few centimetres up to several hundreds of meters with aperture varying from a few centimetres to several meters. Intrusion geometry may be linear, stepped, scalloped, multi-layered, segmented, irregular and combinations of these. Some sandstone intrusions extend laterally for several kilometres and are directly comparable to features seen in the subsurface. Saucer-shaped geometry is most commonly recognized and has plan-view width sometimes in excess of 2 km and transects up to 400 m of stratigraphic section. At their deepest point saucers are connected to a parent unit. Laterally the saucer-shaped intrusions are initially close to bedding parallel or cross-cut bedding at a low angle. Further from the base, saucer geometry becomes steeper eventually cutting bedding at a high angle, producing features commonly referred to as wings. At their outer margins, wings may form close to bedding-parallel intrusions or, less commonly, dykes. Saucer-shaped intrusions are fed by underlying dykes that contribute sand to the saucers. Jack-up of host strata is typical and may be diagnostic of saucer-shaped intrusions and is related to the local increase of rock volume caused by the emplacement of sand. Jack-up is recognised where intrusions step up in the stratigraphy and horizons/intervals can be correlated on both the sides of the intrusion.

NOTES:

Injectite network architecture controlled by host rock anisotropy

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Sandstone injectites reported from deep-marine slope settings typically intrude into surrounding mudstone-dominated units. However, the role of the heterogeneity and anisotropy of the host mudstone on the architecture of subsurface intrusion networks are poorly understood. This study utilises the well-constrained palaeogeographic and stratigraphic context of exhumed clastic injectites in the Nanaimo Basin, Canada, to examine the relationship between injectite architecture and host strata character. Injectite networks are present within mud-dominated strata adjacent to large (kilometres wide, 100's metres deep) Late Cretaceous submarine slope valley systems. In several locations, injectites are identified in the homogenous matrix of thick mud-prone debrites within the confined of slope valleys (Fig. 1). These injectites form networks with a strong preferred strike orientation that is sub-parallel to the orientation of the slope valley, sills are absent, and dyke angles vary between 30° and 90° with a strong trend towards sub-vertical intrusion angles. In contrast, where injectites intrude into laminated mudstone units below or adjacent to the slope valley systems (Fig. 1), the angle of dip ranges from 0° to 90° in a dense network of sills and dykes, with no strong preferred orientation of strike. In both situations, the injectite networks have similar thicknesses and grain-size ranges, and occur in the same stratigraphic interval in the basin-fill. Therefore, the marked difference in their architecture is interpreted to be due to the character of the host lithology. The anisotropy of the laminated mudstone promoted the intrusion of sills, and dykes with a range of orientations, whereas the (relatively) anisotropic properties of the muddy debrites resulted in dykes with a narrow range of orientations that were controlled by the location and orientation of the parent sandbodies. Understanding the controls that the heterogeneity of the host lithology can have on injectite architecture in deep marine settings is important in improving the prediction of the location, and accurate modelling, of clastic injectite network architecture in the subsurface.

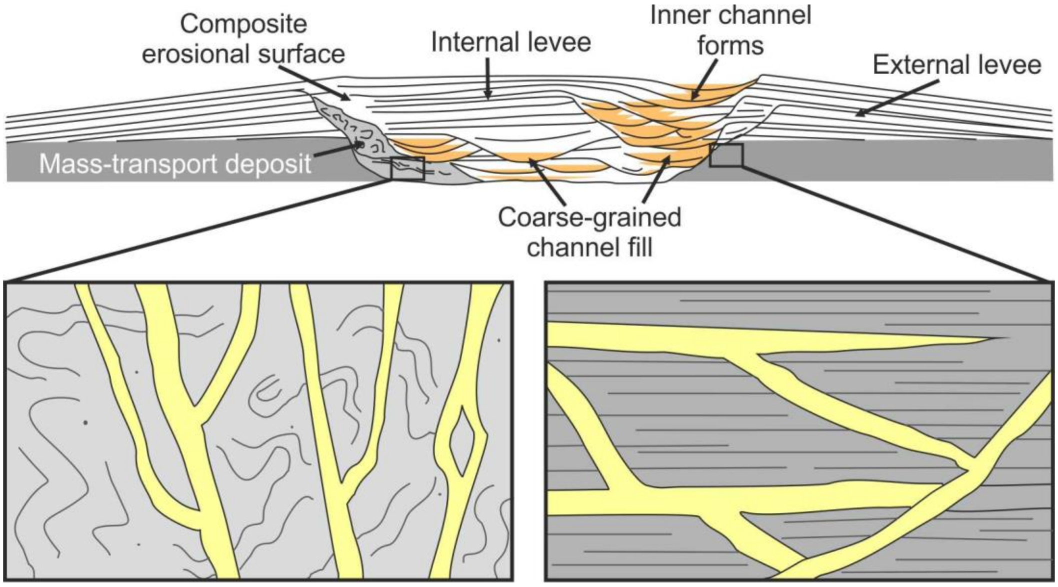

Figure 1: (A) Cartoon of the Late Cretaceous slope valley systems of the Nanaimo Group. The orange represents coarse-grained component of the fill (adapted from Bain and Hubbard, 2015).

NOTES:

Petrography and mineralogy of sandstone intrusions: diagnostic criteria for process and provenance

Andrew Hurst[1], Andrew Morton, Anthony Scott and Mario Vigorito
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Only when sand injection complexes have very-large high-quality exposure can one begin to make confident deductions about the relationships between intrusions and their parent depositional sandstones. Elsewhere, which includes the subsurface, this is a process fraught with uncertainty. By using well-exposed outcrops it is possible to establish robust criteria that allow inference of dominant flow processes during sand fluidisation and injection and, to develop robust diagnostics of provenance. Flow processes are dominantly turbulent and can be inferred from erosional modification of the host strata by intrusions. This is further validated by features such as occurrence of granular micro-fractures, embedding of quartz grains in mud(stone) clasts and, density segregation of grains. Relationships between mineralogy and provenance are particularly useful, specifically heavy mineralogy and single-mineral chemistry, for example, the zircon:tourmaline ratio (ZTi) that increases upward in a dyke system and, the abrasion characteristics of "soft" minerals such as apatite. Single-mineral chemistry allows parent units to be identified in outcrop and subsurface studies, for which examples are provided. In the absence of excellent outcrop that demonstrates physical connection between parent units and intrusions, petrography and mineralogy typically provide strong diagnostic evidence of spatial and temporal physical relationships and should whenever possible be used to constrain parent-intrusion relationships.

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An integrated model of clastic injectites and basin floor lobe complexes: implications for stratigraphic trap plays

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The enigmatic character of clastic injectites increases the need for a wider, and more predictive understanding of their formation and geometry across outcrop- and subsurface-scales. The distribution of subseismic scale injectites and their relationship to those of a seismic-scale are poorly understood. The literature is dominated by examples of clastic injectites that are associated with primary deposits on a slope setting, such as deep marine channel-fills and intraslope lobes. In contrast, injectites demonstrably sourced from base of slope and basin floor sandbodies have rarely been documented.

This study utilises the well-constrained palaeogeographic and stratigraphic context of three outcrop examples exposed in the Karoo Basin, South Africa, to examine the relationship between abrupt stratigraphic pinchouts in basin-floor lobe complexes, and the presence, controls, and character of injectite architecture. Injectites in this palaeogeographic setting occur where there is: (i) sealing mudstone both above and below the parent sand to create initial overpressure; (ii) an abrupt pinchout of a basin-floor lobe complex through steep confinement to promote compaction drive; (iii) clean, proximal sand beds aiding fluidisation; and (iv) a sharp contact between parent sand and host lithology generating a source point for hydraulic fracture and resultant injection of sand. These observations allow an integrated model of injectites in basin-floor lobes to be proposed (Fig. 1).

Injectites are observed to form preferentially at the updip margins of basin-floor lobe complexes and on lateral margins where the pinchout is abrupt and sand-prone. This geographic distribution is linked to the nature of the triggering mechanisms. The presence of patterns on fracture surfaces, the absence of significant compaction of these structures, and the evidence for confined laminar flow, suggest that these injectites formed at substantial depths, but the extensional nature of fracturing indicates a maximum depth of no more than a few hundred metres. Consequently, disequilibrium compaction and lateral pressure transfer are the likely trigger mechanisms, and in the case of a lobe complex deposited above a basinal slope, these mechanisms will lead to updip fluid migration. Furthermore, in a tilted sandbody the confining lithostatic pressure will also decrease updip. Therefore, hydraulic fracturing will predominantly occur at the up-dip margin where fluid migration and the lowest confining pressures combine. Within the proximal lobe complex, injectites are shown to occur at pinchouts; these areas both concentrate fluid-flow from lateral transfer and provide sharp boundaries at their basal surfaces between clean sands and the underlying mudstones.

Initiation of hydraulic fracturing is favoured at the bases of these pinchouts because these clean sands are the most susceptible to fluidisation and therefore will preferentially infill any hydraulic fractures that occur. Theoretically, hydraulic fracturing might be expected to occur on the upper surface of the most up-dip point, as shown in some examples, but in many cases proximal parts of lobes exhibit a transition towards lower permeability facies (e.g., thinner bedded siltstones and sandstones) at their tops. The distal parts of basin-floor lobes are not favoured sites for injection as a consequence of their down-dip position, and their more heterogeneous, mud-rich, facies including thin-bedded silts and sands, and hybrid beds. Whilst the physical linkage between sills and the parent sands suggests that the initial hydraulic fracturing and injection can be downwards, the increasing lithostatic pressure below the parent sands will encourage lateral propagation with sands able to step beyond the lobe complex margins. This is supported by the direction of injection flow being at a high angle to the orientation of sand pinchout. The dykes at all three study sites are aligned sub-parallel to the strike of the palaeoslope which suggests that a controlling factor in injectite morphology is the orientation of the slope onto which the lobes onlap. Tensile features would preferentially develop perpendicular to slope facing direction in a gravitational stress field, leading to a narrow range of dyke orientations after injection was triggered. We demonstrate that for injectites sourced from lobe complexes in tectonically quiescent basins, palaeoslope can be a controlling factor on injectite orientations.

Understanding the mechanisms that determine and drive injection is important in improving the prediction of the location and character of clastic injectites in the subsurface. Here, we highlight the close association of basin-floor stratigraphic traps and sub-seismic clastic injectites, and present a model to explain the presence and morphology of injectites in these locations.

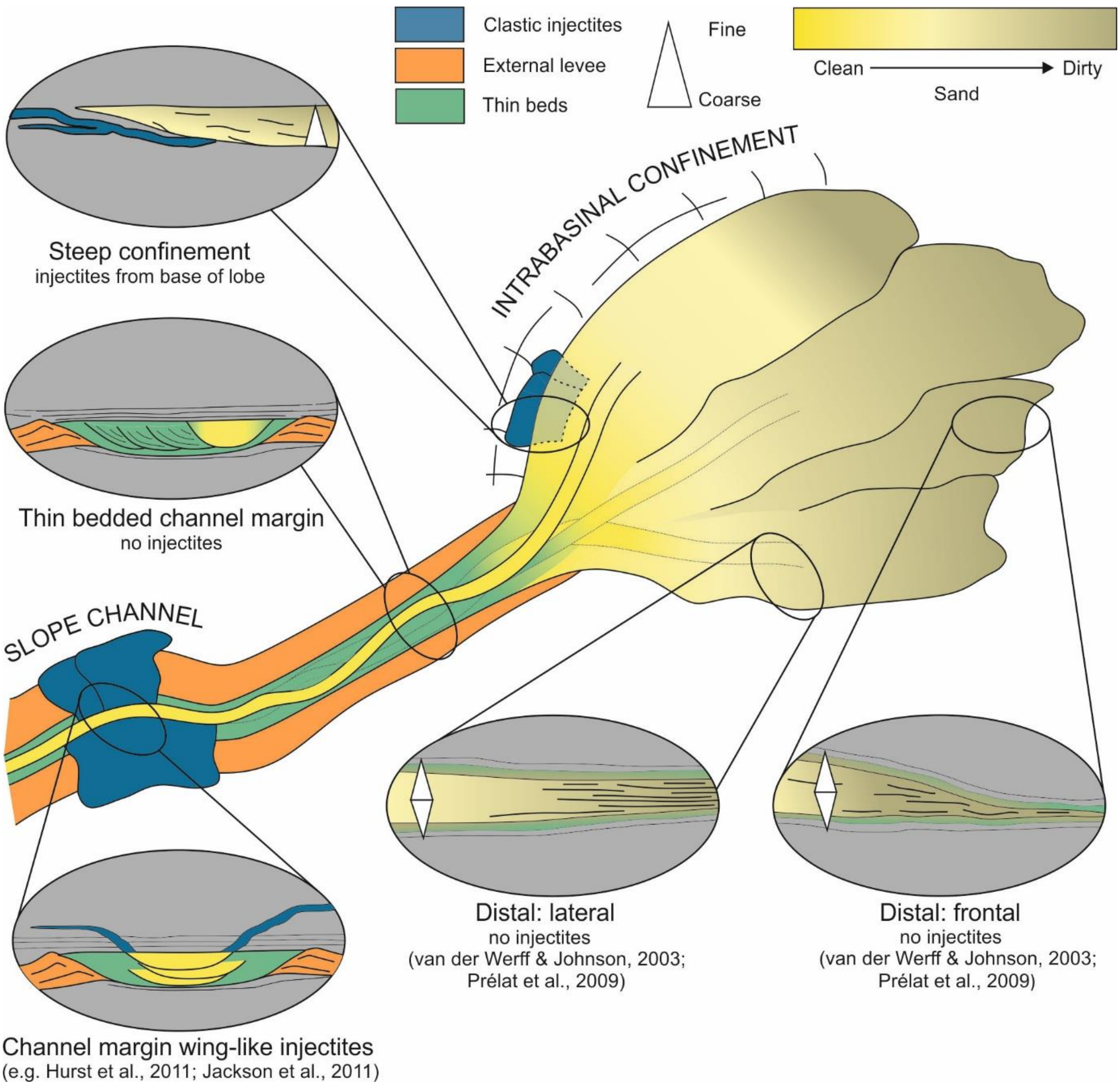

Figure 1. Schematic diagram to indicate likely areas of injection in a deep marine system; examples of previously reported clastic injectites occur on the slope (note that injectites in this setting may be more broad ranging), whereas this study reports examples from basin-floor lobe complexes. Injectites occur in areas where sand is steeply confined and/or proximal within the lobe complex, while palaeogeographic locations that are downdip exhibit subtle confinement or have less clean-sand for fluidisation and therefore do not produce injectites.

NOTES:

Fluidisation pipe dynamics and associated extrudites: An experimental approach

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School of Computing[1], School of Earth & Environment[2], School of Chemical and Process Engineering[3], University of Leeds, Leeds. LS2 9JT.

Fluidisation pipes are known to reach the surface and form extrudites. The same mechanism has also been linked to the genesis of some fluid escape pipes and their associated pockmarks. However, despite increased recognition of the scale and importance of such fluidisation-related structures, understanding of the processes controlling sand injection remains poor, with mechanisms being inferred predominantly from outcrop and core studies. Furthermore, the linkage between processes and the resulting sedimentary deposits is weakly constrained.

This study employs bespoke laboratory experiments to consider the formation of water-fluidised pipes and extrudites, the generated fluidisation sequences and resulting geological structures of a homogenous, saturated, bi-disperse mixture. The experimental configuration is shown in Figure 1. The sediment used was glass ballotini® with a sphericity of 0.91. The fine particle class constituted 40% of the mixture and had a median diameter of 51µm (d_{10} = 38µm, d_{90} = 62µm). The coarse particle class constituted the remaining 60% of the mixture and had a median diameter of 750µm (d_{10} = 634µm, d_{90} = 936µm). A 250mm-thick sediment bed was formed by first dry mixing the particle classes, adding water to form a slurry and agitating to ensure saturation. The resulting slurry was then transferred to the tank in 5mm increments and manually agitated to achieve homogeneity and remove trapped air. Water was then pumped through the central inlet pipe (diameter 8mm) at 0.17ms^{-1} for laminar runs (Re = 350−1300) and 0.89ms^{-1} for turbulent runs (Re = 2000−7000). A digital video camera recorded the fluidisation process at 30Hz.

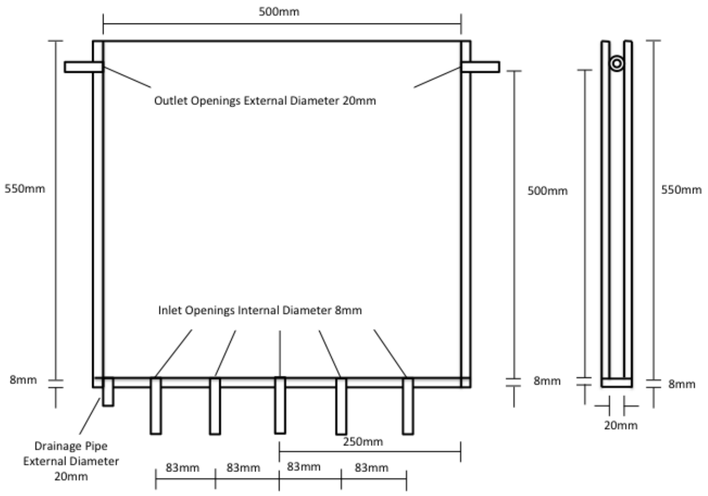

Figure 1 Front and side elevations of Perspex tank with dimensions. Bi-disperse beds, 250 mm depth, were fluidised through the central inlet pipe at velocities implying both Reynolds laminar and Reynolds turbulent flow regimes.

Fluidisation occurred for experiments with Reynolds numbers that implied both laminar and turbulent fluid flow (Fig. 2). Both flow regimes followed the same fluidisation sequence and left a geometrically similar geological structure post-fluidisation. However, the time-scale for fluidisation was significantly reduced in the turbulent regime (Fig. 2). The experiments show that venting to the surface of fluidisation pipes can be a very dynamic process, with potential for complex sedimentary deposits if the venting period is short. If fluidisation is sustained then pipe deposits reach a similar stable geometry. Winnowing of finer-grained materials occurs over a considerable period of time, leading to clean sands in the pipes, and extrusion of the fines into the overlying water column. Further experiments will consider the effects of changing the fines content and the inlet velocity, and the relative location of the inlet within the fluidised zone.

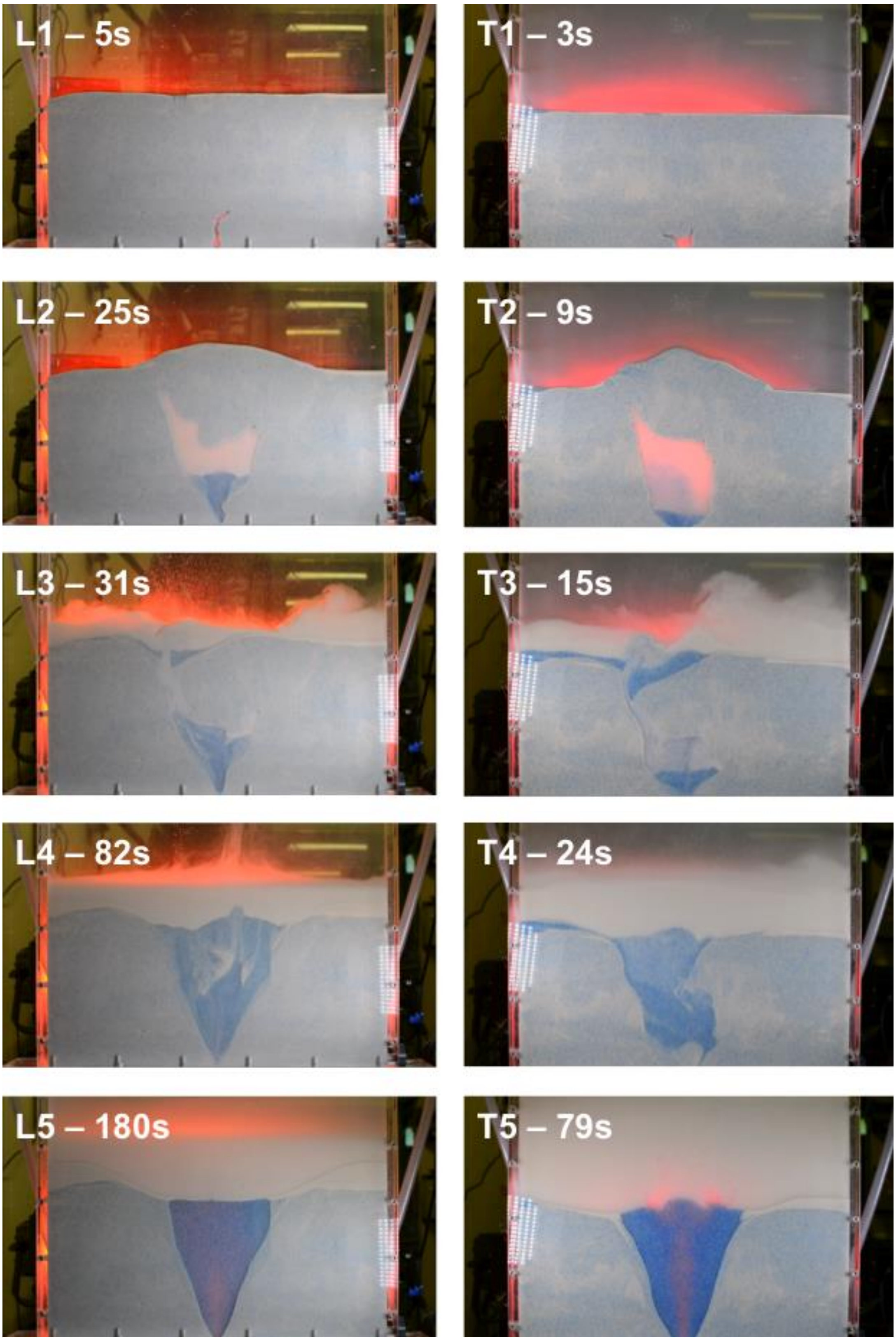

Figure 2 Visualisation of fluidisation processes for both Reynolds laminar (left) and Reynolds turbulent (right) flow regimes. The fine particle class was dyed blue, while the coarse class is white. Stages show L1,T1 - Hydraulic fracture; L2,T2 - Erosive jet; L3,T3 - Collapse of overbed following extrusion; L4,T4 - Erosion of internal structure following a second extrusion; L5,T5 – Stable system.

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Thursday 23rd March

Session Three

Evidences of multi-phase Balder sand remobilization and injection on the Western margin of the South Viking Graben

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The Upper Paleocene/Lower Eocene of the South Viking Graben is host to several large-scale oil and gas fields hosted in deepwater sandstones, many of which have undergone extensive post-depositional remobilization and injection (Hurst & Cartwright (eds) 2007; Huuse et al. 2004; 2007; (eds) 2010). The occurrence of sand injection is significant for exploration, appraisal and development as demonstrated by fields hosted within the Balder Formation, including Gryphon, Leadon and Volund. In these fields significant reserves are hosted within sandstone dykes and sills emanating from both sides and crests of thick massive sandbodies whose origin have been debated for over 20 years. Using legacy and modern broadband 3D seismic data, we aim to better constrain processes responsible for sandstone actual architecture within the Bader formation, demonstrating that their present geometries are the product of multiple superimposed remobilization events at various stage of burial. This new model may have significant implications for future exploration and development in the North Sea Paleogene where similar feature have been observed in the Outer Moray Firth, Central Graben and North Viking Graben.

Mass-transport deposits are sedimentary, stratigraphic successions that were remobilized after initial deposition but prior to substantial lithification and transported downslope by gravitational processes. Mud–prone mass-transport deposits are from far the most common type of mass-transport deposits in deep-water settings 90%. Given the common presence (10%) of sand-prone mass-transport deposits in shallow subsurface and outcrops, the lack of prevalent examples from producing fields is likely due to misinterpretation rather than non-occurrence. Moreover, recent studies have shown that sand-prone mass-transport deposits can contain high-quality reservoir sands, porosity can be in excess of 30%, and permeabilities on the order of several darcies, confirming that they can act as significant reservoirs in oil and gas fields (Mannaerts, et al., 2005; Winker et al., 2007; Meckel, 2012).

In the North-Sea, mass transport deposits have been poorly described, only few examples have been published (Jennette et al., 2000, among others). The Eocene aged Balder formation represents an important stratigraphic marker within the European's offshore sedimentary record, occurring over large areas of NW Europe. Economically, it is an important in both forming effective top seals across the North Sea and Faroe-Shetland basin, and additionally represent under exploited reservoir intervals. Despite its significance as a stratigraphic hydrocarbon trap and its role in top seal to older plays in the North Sea offshore sedimentary basin, modern 3D seismic data show that this formation still holds secrets of geological and economical importance, despite over 50 years of exploration in the North Sea.

Using broadband 3D seismic and well data, we re-investigate the late-Paleocene – Early Eocene and especially the Eocene Balder formation on the western margin of the South Viking Graben to highlight the occurrence of sand-prone mass-transport deposits. They occur over large areas (>100km long and 40 km wide) affecting most of the Balder formation fields in this area (Volund, Gamma, Leadon among others). We observe that individual sandy blocks can be few kilometres long and wide (Fig. 1) and tens of metres thick thus involving sandstone volumes of 1-3*10^8 m^3. Many of these isolated sandy blocks called "Odin sandstones" in the literature can be considered as out runner blocks sliding on the top of the Dornoch delta. We demonstrate that this area has been subjected to at least two superimposed submarine deformation episodes, the latter associated with extensive sand injection, likely sourced from underlying Paleocene Heimdal sandstone, remobilizing and injecting sands across the tuff- and clay-dominated Balder and Frigg formations. We constrain the timing of these different events and for the first time we illustrate the occurrence of contractional features affecting the balder formation (fore- and back- thrust, and vertical shear zone). This study forms part of a whole-basin assessment of remobilization and injection events, which highlights the repeated occurrence of submarine landslides, their burial and remobilization and injection of sand.

The new insights regarding early and late-stage remobilization will inform and guide future exploration and development in the North Sea Paleogene and beyond. The new models will ensure that more appropriate geological models can be constructed that take into account both depositional and subsequent remobilization processes. The lessons learned in the North Sea are portable and informs early observations in frontier exploration provinces along the Atlantic and Indian Ocean margins.

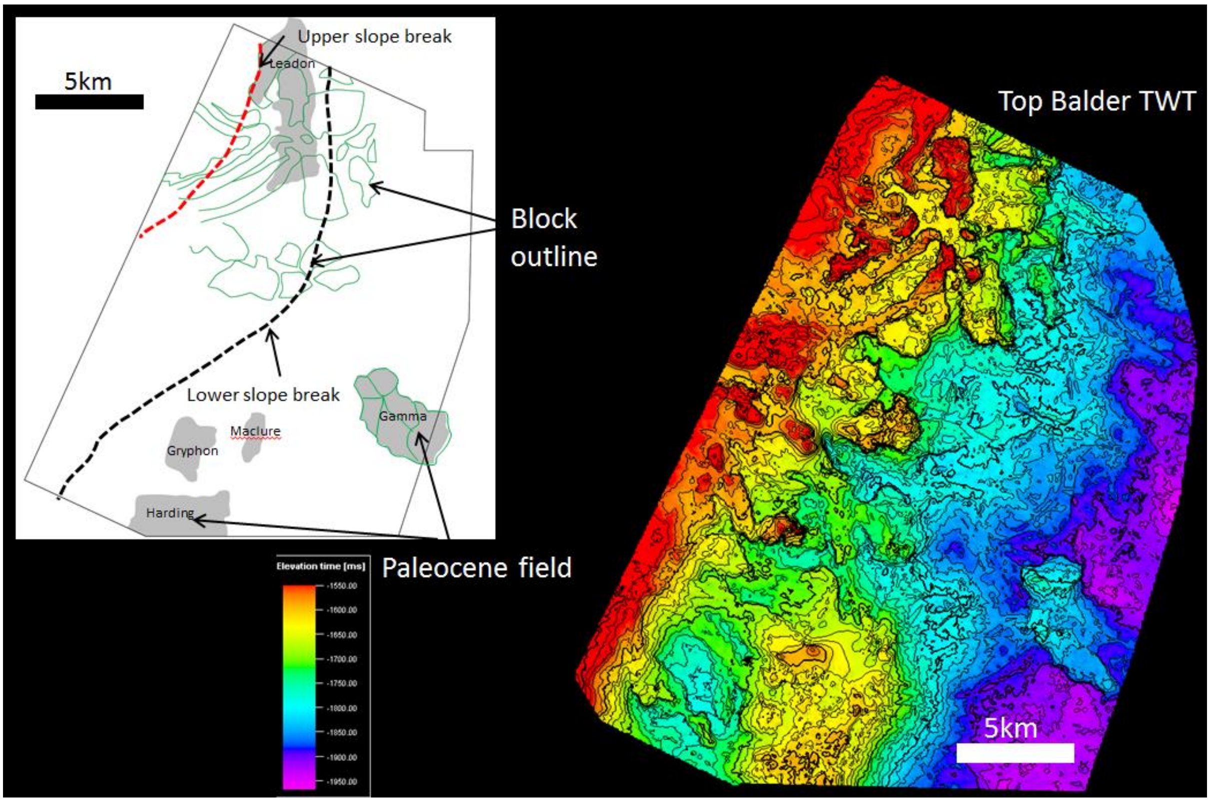

Fig. 1: On the left, line drawing of the study area showing the distribution of isolated sandy blocks within the Balder Fm., note Paleocene fields for location. The upper and lower slope breaks of the underlying Dornoch delta are highlighted. On the right, top Balder map (TWT) showing intriguing relief anomaly geometries mainly north of this study area.

Acknowledgements

MegaSurvey and Geostreamer 3D seismic data were provided courtesy of PGS. We are further grateful to TGS for access to their Facies Map Browser, to Schlumberger for Petrel software and to Eliis for access to Paleoscan. This work forms part of the Sand Injection Research Group JIP whose sponsors are gratefully acknowledged. Several students and colleagues in academia and industry helped shape the ideas presented herein, perhaps most notably Mark Reeder, formerly at Kerr McGee North Sea who first pointed out the jigsaw-like appearance of the Balder Fm.

NOTES:

The Paleogene eastern North Sea – a dynamic setting for subsurface sand remobilization: established concepts on distribution and controlling factors

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Recent research on the Paleogene succession in the Norwegian-Danish Basin has led to the recognition of remobilized sand features at four locations within an area approximately 100 km wide (Fig. 1). The four locations of remobilized sand show significant differences and have likewise been suggested to form due to slightly different mechanisms (Table 1).

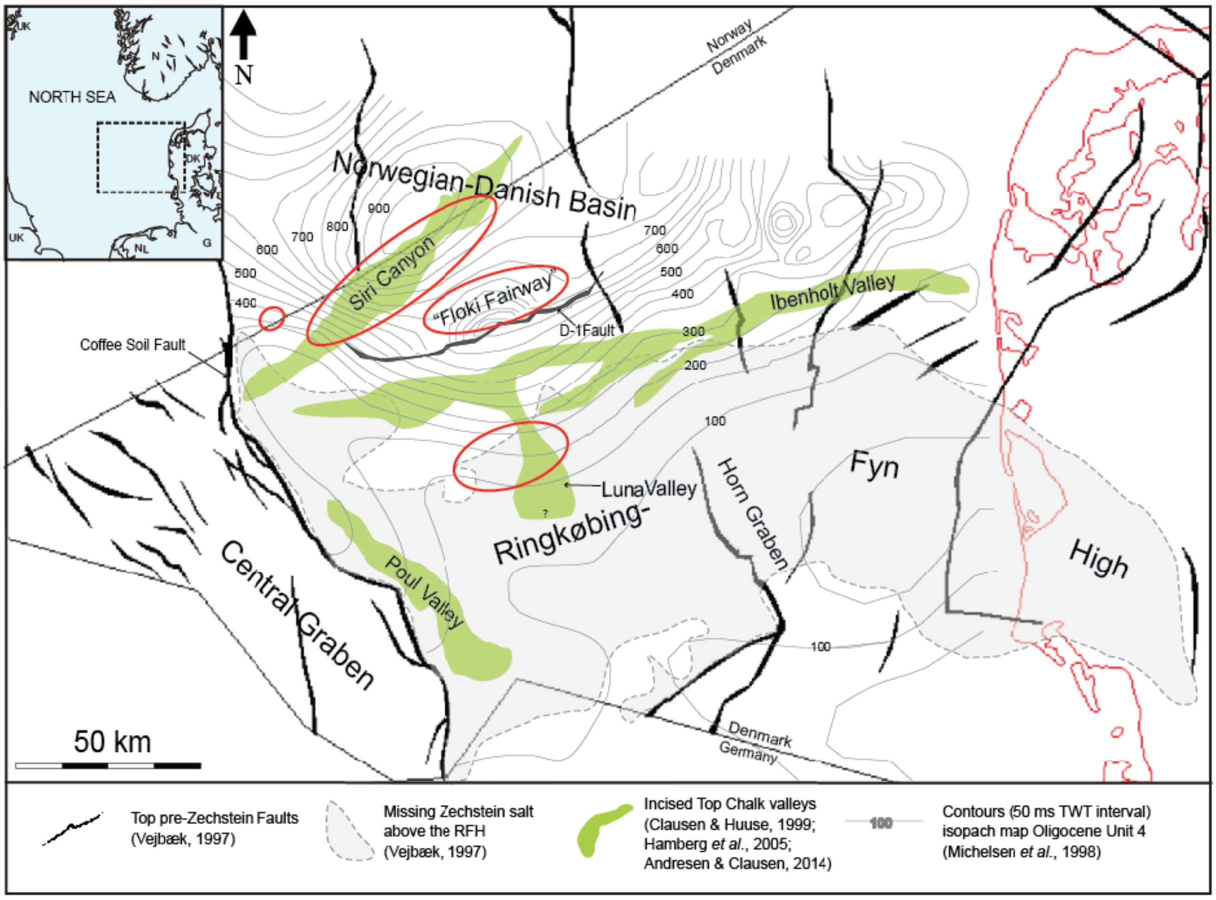

Figure 1: Overview of the study area and the four locations (red ellipses) of remobilized sand features The first group of subsurface sand injections is described from the Paleocene incised Siri Canyon where remobilized gravity flow sand now constitutes the key reservoir for several oil fields within the canyon. The injected sand can be characterized as a result of 'short-distance' remobilization where the remobilized parent sand body is connected to sills and wings typically protruding along faults in both an upward and downward direction. The remobilization of the Siri Canyon sand has been suggested to occur shortly after deposition triggered by the deposition of overlying hemipelagic to pelagic mud and marl stone members and tectonic activity in underlying salt structures (Svendsen et al., 2010).

The second group of injected sand features is found in relation to a similar incised valley in the top of the Chalk Group, the Luna Valley. At this location, large conical to saucer-shaped intrusions are observed. The injected sand reflects 'medium-distance' remobilization where the intrusions are now fully separated from the source sand succession. Overpressure build-up which triggered the remobilization and formation Page **2** of **3** of the sand intrusions is interpreted to result from a combination of 1) differential loading and lateral transfer of pressure in relation to rapid southward progradation of clinoforms and 2) deep thermogenic fluid migration from underlying Paleozoic half-grabens (Andresen & Clausen, 2014)

The third group of remobilized sand is observed in an area informally termed the 'Floki Fariway' in between the Siri Canyon and the Luna Valley. This group shows the classic depositional channel sand remobilization where injected wings are observed along the sides of the channel. Core and cutting analysis confirm the remobilized nature of the channel fill and the controlling mechanisms have been suggested to result from depositional processes including rapid and differential loading causing disequilibrium compaction and/or lateral transfer of pressure. Reactivation of a nearby large fault and associated thermogenic gas migration may have further enhanced the overpressure build-up in the system (Andresen et al., 2013).

The fourth group of remobilized sand relates to a proposed sand extrusion exemplifying 'longdistance' remobilization above a sub-segment of the Siri Canyon. The trigger mechanisms for the sand extrusion have been suggested to relate to differential loading and lateral transfer of pressure combined with lateral thermogenic hydrocarbon charging of the Siri Canyon where the suggested source sand was located (Andresen at al., 2009).

Area	Siri Canyon	Luna Valley	Floki Fairway	Siri Canyon Overburden
Nature of injected sand	Fault-guided, upwards and downwards injected sills and wings	Conical to saucer-shaped intrusions	Injected wings at the sides of depositional channel fill	Extrusion, layered
Source sand	Paleocene and Eocene	Paleocene	Eocene	Paleocene or Eocene
Host rock	Paleocene and Eocene	Eocene and Lower Oligocene	Eocene	Extruded at the Mid Miocene Unconformity
Nature of remobilization	Short-distance	Medium-distance	Short-distance	Long-distance
Timing of remobilization	Paleocene and Eocene	latest Early Oligocene to Late Oligocene	Oligocene	Mid Miocene
Trigger mechanisms	Deposition of overlying mud- and marlstones, tectonic activity in underlying salt diapir	Differential loading, lateral transfer of pressure, thermogenic fluid migration	Disequilibrium compaction, differential loading and lateral transfer of pressure, fault reactivation, thermogenic gas migration	Differential loading, lateral transfer of pressure, lateral migration of hydrocarbons and charging of the Siri Canyon

Table 1: Summary of the characteristics for the four groups of remobilized sand.

The four different groups of sand injection features highlighted in this study demonstrate the variability in the nature of remobilized sand. All four groups reflect remobilization of discrete Paleocene or Eocene source sand bodies which all, most likely, were brought into the area by gravity flows originating from the north-east. The gravity flows were guided by the presence of existing incised valleys and by underlying active salt structures. The varying source sands were remobilized under different circumstances leading to differently expressed remobilized sand features. In three of the cases, differential loading appears to be a major controlling factor for the remobilization, and thermogenic fluid migration has similarly been suggested to be a contributing factor. Hence, the eastern North Sea appears to be a remarkable dynamic setting for subsurface remobilization, where discrete depositional sand bodies have been remobilized during several major phases of local overpressure build-up which often relates to the continued rapid and Page **3** of **3** differential loading and filling of the Norwegian-Danish Basin during the Oligocene and Miocene. Realizing and understanding the complexity of such a dynamic remobilization area is critical for predicting the location of more sand intrusions and potentially for understanding the fluid migration system in the area.

NOTES:

Sand remobilisation and the petroleum system of the Brimmond Fairway.

Lyndsay Singer
Apache Corp

The Eocene Brimmond Formation turbidite fairway is situated along the North-eastern flank of the Palaeocene Forties structure (UKCNS blocks 21/10 and 22/6). The deposition of this fairway was focused by seafloor topography created by older Palaeocene turbidite systems over the Forties Montrose High. It ends in a terminal lobe South-west of the Nelson Field. Located along the western margin of this Brimmond fairway are well imaged remobilised sands that form the reservoir interval for the Maule and Tonto Fields and, along with deep-water channels, the Brimmond Field. These Eocene Brimmond sands are encased in the Horda Shale which provides the sealing lithology.

The interpretation of these remobilised and injected sands is driven from geometries derived from 3D seismic and historic logging of thin sands in the Eocene interval. Conical shape features emanate from the top of the Forties sandstone with steep dikes and sill wings, with seismic evidence of injection along active faults and fractures. The Western/South-western flanks of the fields are stratigraphically trapped by the Horda Shale with the other flanks dip closed. A study of the heavy mineral and detrital garnet geochemistry identified that the Eocene Brimmond system was the parent unit for these remobilised sands. Fluid data obtained from a Maule PVT sample suggests that it is likely the oil is sourced from the Kimmeridge Clay Formation and possibly charged by vertical migration from the Forties field through these Eocene remobilised sands.

The developments of the Brimmond, Maule and Tonto fields has been successful due to impressive seismic imaging with inversion and Direct Hydrocarbon Indicator (DHI) volumes allowing the identification of hydrocarbon bearing remobilised sands, along with 4D data imaging un-swept areas.

Sand injection processes have played an important part in both trap and migration pathway provision for the Brimmond system. By understanding these processes and interpreting the Brimmond fairway and associated remobilised sands, the Brimmond, Maule and Tonto developments have helped to rejuvenate the giant Forties Field.

NOTES:

Seismic expression of a large injectite complex, Great South Basin, New Zealand

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A large injectite complex has been identified within the Paleocene succession of the frontier, deepwater Great South Basin offshore New Zealand. A recently acquired 3D marine seismic survey, constrained by sparse well data, has enabled the basin stratigraphy to be dissected, revealing Late Cretaceous to present day deepwater gravity flow channels which drain eastwards from a sandy continental shelf. The depositional systems pond against topographic highs within the mud-dominated basin located adjacent to the transtensional Australian-Pacific plate boundary.

Seismic facies analysis has revealed a 160 km2 amalgamated injectite body linked by numerous dykes to the underlying deep-marine channel deposits, which are interpreted to be the source of the observed remobilisation. The large-scale channel features, occurring at a number of stratigraphic levels 100-500 m below the injectite, can be clearly traced into the vicinity of the feature, but appear to terminate abruptly below it. Seismic geobody extraction indicates that the volume of the injectite is consistent with the volume of the ‘missing’ channel bodies.

Drilled sub-surface injectite analogues from the North Sea and outcrop analogues are compared with this complex and reveal similar morphologies and dimensions. This injectite is one focus of Woodside’s exploration effort in this frontier area and represents a rare example of an injectite being a primary exploration target.

NOTES:

The Structural and Stratigraphic Evolution of the Catcher Area Injectite Complex

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Premier Oil

The Catcher Area hydrocarbon accumulations are located on the Western Platform of the Central North Sea, largely in UK Block 28/9a. There are numerous stratigraphic traps, containing moderately biodegraded oil and associated biogenic gas, with the largest volumes contained in the Catcher, Varadero and Burgman Fields.

The reservoirs are Palaeocene/Eocene in age, located above and below the Balder formation, and are unconsolidated sands with excellent flow properties. Vertical thickness of the main seismically resolvable reservoir interval is typically 20-60ft. Core data and high quality 3D seismic provide compelling evidence for the injected nature of the sand bodies, but there has always been difficulty in proving the extent to which the sands are injected, and in describing the depositional parent reservoir unit. This problem is exacerbated by the relatively weak seismic response of water-bearing sands.

Development drilling commenced in 2015, and has provided an excellent opportunity to focus on well-specific locations and to collect comprehensive appraisal data, thus allowing a more detailed description of the subsurface at a local scale. We will discuss how these new data have helped when re-visiting the pre-development regional interpretation. The current view within the project team is that the deeper Palaeocene ‘Cromarty’ turbidite reservoirs were deformed by extensive salt and fault movement, and subsequently over-pressured, triggering the injection of sand up-stratigraphy into the over-lying mudstones. Injected sands exploited the pre-existing fault network, and terminated at a consistent stratigraphic level, thought to be extruded sands on a palaeo-seabed. The interpretation is therefore that the reservoirs present above the Balder Formation are dominated by injected sands, with little evidence for any significant depositional component.

NOTES:

Evolution of the interpretation of the Volund Field

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[1]*Aker BP ASA*

The Volund Field (Norwegian Continental Shelf) was first drilled in 1993 and discovered a 7m gross oil column. After one appraisal well, the reservoir was interpreted as a deep-marine turbidite fan with non-economic volumes.

In conjunction with the growing appreciation of injected sandstones, in 2004 a new round off appraisal drilling of the field started. A new conceptual model interpreted economic hydrocarbon volumes located in the flanks of the reservoir within injected sandstones dykes. The appraisal drilling consisted of one main bore and after its discovery three additional laterals to explore the down- and up-flank variability in thickness, facies, reservoir quality and tie to the seismic along the sandstone injection. This interpretation proved to be true with a 104 m gross oil column with a gas-cap found. This initiated a field development project with first oil produced in 2009 and continues today.

Since 2004, the interpretation of the field being injected remains; however, the complexities of the injectites are better understood with improved seismic imaging, more well penetrations, studies of outcrops, 4D seismic, chemical tracers and production data. Some key evolutions in the interpretation and the resulting consequences include:

1. As seismic imaging improves and utilisation of multiple surveys with contrasting shooting directions, more injected dykes are imaged. This has led to an increase in STOIIP estimates which is now more in line with historical production data and forms the basis for better production forecasting.

2. Injected sandstone dykes are more composite and bifurcating in reality than originally interpreted. This is now partly recognised on seismic data, supported by well penetrations and production data and can be visualised in outcrops examples. Dykes not penetrated by production wells are potential targets for infill drilling to increase reserves.

3. All dykes link downwards to a parent sandstone body unless there is clear evidence of post-depositional events to break this connectivity. In Volund area this is the Heimdal Fm. containing a large active aquifer. This understanding is applied to estimating pressure and water movement within the composite dykes during the field’s productions. Consequential actions to reduce water production and target higher pressures parts of the field can be taken.

4. In areas between mapped injectites, there will often be a network of connecting, subseismic dykes and sills. These contribute to the STOIIP and reserves and help with aquifer support. In addition, these should be identified during drilling operations as unmapped reservoirs as both drilling “hazards” but also opportunities to drain additional reserves.

As with many fields, a multi-disciplinary approach to interpreting the characteristics on the reservoir is key to maximise reserves. In reservoirs from injected sandstones such as the Volund Field, this is especially true given the less predictable nature of the reservoir distribution.

NOTES:

The Heimdal reservoir of the Mariner Field – the value of integrating new broadband seismic and existing well data

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Statoil Production UK Ltd, Aberdeen.

The Mariner Field is located on the margin of the East Shetland Platform. It comprises two Palaeocene reservoir intervals - the Maureen Fm, and the Heimdal Sandstone Member of the Lista Fm. The Maureen Fm is a high NTG (~0.8) reservoir and comprises sand and mixed sand-carbonate lithologies. It was deposited in a slope/ canyon setting as multiple stacked turbidite lobes, channels, and slump units. It is probable that some Maureen Fm was remobilised by post-depositional injectite processes. The younger Lista Fm is a lower NTG (~0.1) and is dominated by slope clays and silts. Turbidite deposited/ remobilised and injectite sands form the Heimdal Sandstone Member reservoir. Both reservoirs are unconsolidated, with the exception of carbonate cemented lithologies.
Prior to Statoil acquiring operatorship, post-depositional injectite processes were considered likely to have occurred in the Heimdal of the Mariner Field, but the impact was less understood. Since Statoil took over operatorship in 2007 the acquisition of new seismic data and the re-analysis and integration of existing well data has been used to address a number of technical challenges which have historically impacted the subsurface evaluation of the Heimdal reservoir – including the impact of injectites. As with similar complicated projects the value of integrating numerous datasets has significantly improved understanding of the reservoir, improved definition of subsurface uncertainty and allowed the planning of development wells in seismically resolved targets.
Maureen Fm pre-development drilling started in late 2016, prior to the arrival and commissioning of the top-sides. Appraisal drilling on the field is planned during the commissioning phase, which includes the planned acquisition of Heimdal core and sonic and density data in the Lista Fm. Following commissioning and appraisal drilling the main development drilling of the Maureen and Heimdal will then proceed.

<u>The importance of mapping seismically defined geobodies</u>

A wide variety of seismic datatypes, including traditional streamer data, broadband and ocean-bottom seismic, were acquired over the Mariner Field in the period 1995-2012. These have been variously processed in the time and depth domains, including velocity models derived from tomography and full-waveform inversion. A broadband survey shot in 2012 has proven the key seismic volume used during development planning. In-house pre-stack inversions for nears and fars were used to generate an AVO volume. An automated method was not used to extract Heimdal sand geobodies from the AVO volume due to the overlap of responses for oil and water-filled sands. Instead, a user guided point-set interpretation was generated within pre-defined relative impedance ranges. This was subsequently incorporated into the geological models as a set of geobodies. The interpreted geobodies comprise complex and locally labyrinthine sand architectures which broadly tie to well-log derived observations of Heimdal reservoir. The tying of inversion-derived geobodies to equivalent sands penetrated in wells is complicated by a number of factors including the upscaling of the well-logs to seismic scale, lateral seismic location uncertainty and the complexity of the injectite geometries. However, Heimdal sands are resolved and many wing-shaped and sill injectite geometries are identified - and these are expected to provide connectivity within the Heimdal. Production and injection wells have been planned within the Heimdal geobodies and subsequently used in simulation modelling. The importance of the mapped geobodies has been very significant in reducing project uncertainty as it allows well targeting within Heimdal sands, whereas previously no targeting could be done with confidence.

Prior to broadband seismic, it was thought likely that injectite processes had impacted only the Heimdal reservoir. Subsequent mapping of seismically resolved wings/ dyke complexes emanating from the top Maureen also suggest that the Maureen, at least in part, was remobilised into the Lista Fm. As several tiers of Heimdal sand are interpreted within the Lista Fm it seems likely that the Heimdal sands themselves also provided a source of sand for shallower Heimdal injectite units. Seismic interpretation of the top Lista Fm also reveals several structural culminations in and around the Mariner Field. These are interpreted as injectite jack-up structures that correspond to areas of thicker Lista Fm. The most notable culmination has been drilled, and well-logs identified Heimdal sands where geobodies are interpreted on the new broadband seismic. It is likely that these jack-ups generated positive sea-bed topography at end Palaeocene/ prior to deposition of the Dornoch Fm. The Dornoch sands have a complex architecture – appearing to be deposited around and overlying the Lista jack-up structure. As such the Dornoch may comprise hybrid depositional/ extrudite sands.

The importance of reanalysing and integrating existing well data

Image log analysis of FMI data from four Mariner wells has also proven valuable in identifying thin-bedded injectites within the Lista Fm and further characterising facies types (i.e. sills, dykes and injectite breccia) and their proportions. Due to the fine scale of these facies, while they were detected on conventional log data (i.e. represented by subtle changes in log character/ trends), they were not accurately resolved. Within the Maureen Fm the same analysis has proven useful in the identification of assessing previous unrealised facies types, bed-sets, candidate correlatable surfaces/ possible flow baffles and defining facies proportions. It is expected that the FMI interpreted facies may be useful in further improving the well-log to seismic tie.

A new correlation scheme has been generated for the Lista Fm by incorporating existing biostratigraphic analyses with a new de-sanded correlation method. As the majority of the Lista Fm comprises clay the de-sanded method has proven useful in identifying clay and silt log motifs which are more likely to be laterally correlatable than depositional/ injectite sands. The resulting correlation scheme has been integrated with seismic reflectivity horizons to provide additional zonal control within the geological model. At some point in the future, as more wells are drilled through the Lista Fm such additional zone definition is expected to be used to control on the facies distribution.

The Mariner Field is expected to produce oil for more than 30 years – and at this stage in the development it is natural that significant subsurface uncertainties exist. Understanding the impact of these uncertainties has been an important input into the development planning.

NOTES:

Thursday 23rd March

Session Four

When 2D just isn't enough: Geosteering a well in a 3D sand injectite environment. A case study from Premier Oil's Varadero field.

Mike Bower[1] , Xu Chonghui[1], Dominic Riley[2], Matt Gibson[2], Cuong Nguyen, Tom Martin[2], Gordon McCartney[2] and Steve Kenyon-Roberts[2]
[1] *Schlumberger*
[2] *Premier Oil*

Large scale sand injectites are becoming a more prominent play in the Oil and Gas developments of the UK North Sea. They are notoriously difficult to visualize in 3D seismic due to their thin and irregular nature, often requiring seismic attribute analysis and processing to enable their resolution at a broad, field scale. It is known from field analogues and seismic interpretation how such features can exhibit highly random, discontinuous and steep geometries, proving a tough challenge in all parts of the field life cycle; with drilling being no exception.

Accurate well placement is becoming more sought after to ensure wells are drilled to maximize reservoir transect; advanced technology and workflows are being used to achieve these results. As with many things, no single piece of information solves the puzzle, merely adding another piece of that puzzle to achieve the end game. More often than not, well placement sees the real-time modification of the well trajectory's inclination without modifying the well's azimuthal direction other than to hit pre-drill determined targets, therefore the lateral position, dip and context of the geology is often not integrated into geosteering decisions. Due to the discontinuous nature of sand injectites, this is not a luxury afforded to geosteering in this environment.

This paper documents a workflow developed by the Premier Oil Catcher asset team in close collaboration with the Schlumberger (Aberdeen) well placement team to successfully increase a well's net:gross by applying geological understanding, in combination with seismic data and the 3D indicators from the latest azimuthal deep reading resistivity tool (GeoSphere).

NOTES:

Improving the image of injectites

Craig Buchan, Roderick McGarva
Task Fronterra

Injected sand reservoirs are notoriously difficult to characterise and model. However, these units comprise significant potential hydrocarbon volumes in North Sea fields such as Alba, Volund, Mariner and Catcher. Seismic analysis can detect the largest geobodies in these systems, but miss significant volumes in smaller scale injection bodies and/or units such as injection breccias which may represent significant upside potential in such fields. In addition, smaller scale injectites, although not important in terms of primary hydrocarbon volumes, can have an important control on reservoir character and fluid flow during development. This is especially the case in terms of geobody connectivity, which can lead to unexpected results during production and potential problems like early water cut.

Traditional open hole logs are also challenged in representing these bodies because the individual injectites may be quite thin and have steep and irregular margins which cannot be detected with these conventional logs. Borehole image logs provide a high resolution representation of the wellbore allowing ready detection and orientation of these sand body types. Images can allow the classification of injectites into sills, dykes and injection breccias with local bed geometries defined on the orientation of the associated upper and lower bounding surfaces along with apparent thicknesses. Descriptive modifiers include the presence of internal fabrics, shale clasts, ptygmatic folding and cementation. In addition, deformation fabrics in parent donor sandstone bodies can sometimes be assessed. These parameters can lead to improvements in understanding of injected sand genesis, formation quality, emplacement timing and connectivity of bodies.

Analysis of sand injectites can include all the techniques applied to conventional fracture and fault populations and surface outcrop studies: stereonets, population statistics, azimuth and strike plots, apparent dip plots and traverse statistics, that all can be used to help understand their origin, occurrence, orientation, connectivity and mutual interrelationships. The data also lends itself well to use in comparison to field analogues because the scale of analysis is the same.

In this paper we will show how image logs can significantly improve the understanding of sand distribution, internal formation quality and orientation of bodies to improve modelling of these complex units. In addition we will demonstrate that image logs can be used to give a more realistic assessment of net to gross in injected sand reservoirs often providing significant increase in estimated sand. Finally we will show that the orientation data generated from borehole image logs can lead to improvements of interwell modelling of injectite continuity and understanding of connectivity of bodies.

NOTES:

A review of the impact of multimeasurement broadband data at the Mariner Field: Model building, imaging and inversion

Mehdi Paydayesh
WesternGeo

The Mariner field is a shallow heavy-oil development field located in the East Shetland platform of the UK sector of the North Sea. It contains two main targets: the Heimdal sandstone members within the Lista shale formation, and the underlying Maureen Fm. sandstone. The Heimdal sands consist of a complex, disrupted channel system of remobilized unconsolidated and uncemented sands and injectites. Seismic imaging challenges create uncertainty in the Heimdal reservoir model, including connectivity between the Maureen and Heimdal sandstone units. Multimeasurement towed-streamer seismic systems can provide data sets that combine temporal broadband characteristics with high spatial resolution. A 220-km2 survey was acquired in 2012 using a broadband, multimeasurement towed-streamer system. This paper summarizes the results of several studies based on this data set. These span from initial processing through advanced velocity model building, depth imaging, and amplitude inversion. In doing so, this provides a good opportunity to review how various technology developments in the last five years have impacted the final interpretation products. The results also point towards a significant improvement in interpretation over the key Heimdal and Maureen reservoir intervals, reducing uncertainty in the reservoir model and guiding field development planning.

NOTES:

Reservoir Modelling of Sandstone Intrusions using modified DFN approaches

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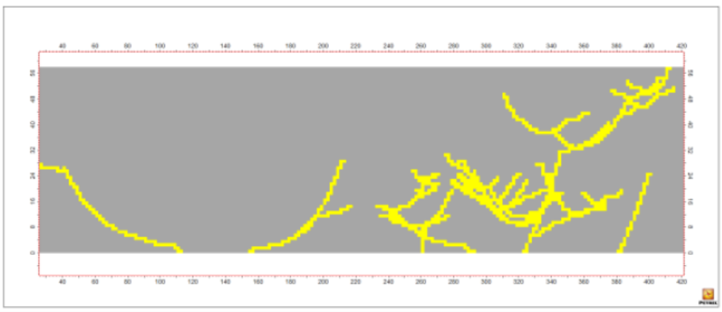
Key words: *sandstone intrusions, reservoir modelling, algorithms.*

Sand injection, the forceful remobilisation and injection of sand during burial, is now recognised as an important component of both new and existing clastic reservoirs. The presence of sand injection features in a reservoir impact reservoir performance by modifying reservoir connectivity away from that expect from the initial depositional architecture. Current reservoir modelling systems, however, have difficulty in representing sand injection features for 2 primary reasons. 1) The injection features tend to be steep angle with respect to the initial stratigraphy with variability in both dip and azimuth, with complex geometric relationships and 2) many of the injection features which will modify the flow regime fall well below typical reservoir modelling resolutions.

To address the first problem we present 2 possible approaches to model sandstone intrusions, one using standard modelling algorithms, and a second using a bespoke modelling approach. For the first approach a Truncated Gaussian Simulation is used to build intrusion geobodies conditioned to locations of parent units, with the initial Gaussian simulation being created using an upscaled parameter from a traditional DFN. The DFN is conditioned to shadow zone parameters derived from the parent unit locations, which will then result in a model where intrusions preferentially connected sand bodies. The resulting truncated simulation gives discrete geobodies which can then be populated with petrophysical parameters. This approach has the advantage of using readily available algorithms, but has the limitation of not being able to accurately model the branch-form nature of the intrusions seen in the field, and does not provide any internal trend data to assist with petrophysical population. The second approach utilises a branching discrete object network approach (a hybrid between a DFN and an object model) which honours conceptual models derived from outcrop observations and allows for more realistic intrusion geobodies, and more crucially the relationships between those geobodies to be modelled. The branching model allows for upward steepening and bifurcation of intrusions, which are relationships often observed in field data. This bespoke approach also has the advantage of allowing a greater degree of control over the population of petrophysical parameters by providing trend data within the modelled objects including intrusion width, and direction of injection. As this new modelling approach produces more realistic intrusion geometries models generated in this way can also be used as input for MPS modelling algorithms.

As the discrete object approach builds the intrusions as tetrahedral bodies, the modelling approach does not require a modelling grid to build the initial model. This means an intrusion model can be built at a resolution much higher than would be possible in a traditional reservoir model at field scale. This model is then up-scaled into a modelling grid to give continuous sandstone intrusion porosity and permeability values.



An example of a model built using the new branching discrete object modelling algorithm.

Sandstone intrusions can be modelled using traditional modelling approaches, and in many cases these will suffice, however in order to maximise the recovery from such reservoirs this new modelling approach would provide more realistic geometry and connectivity with little extra work over than needed from standard workflows.

NOTES:

Seismic Architecture and Genesis of Sand Injectite Complexes, offshore Uruguay

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Sand injectites are common in deep marine clastic settings and have been reported within numerous basins around the world where they constitute important pathways for fluid flow. In addition to being potential hydrocarbon conduits and reservoir elements, the detailed analysis of sand injectites can help provide critical insight into the location, source and relative age of basin overpressure and its potential source. Until recently, seismic-scale sand injectites had only been recorded in the North Sea and central California. This paper reports a series of large-scale sand injectites that are spectacularly imaged by 3D seismic data across an area of c. 13000km^2 within the Eocene-Miocene section of the Pelotas Basin offshore Uruguay.

The sand injectites occur as two distinct complexes that formed at broadly similar times: the proximal complex is located immediately basinward of the palaeo-shelf edge and the more distal complex is located in an upper slope setting.
The proximal complex covers an area of >350km^2 and is located at a present-day depth of approximately 2200mbsl (1100m water depth). The complex resides immediately above a regional marker horizon which marks the start of a period of major sediment delivery into the Pelotas Basin during the Eocene-Miocene period. In plan form the injectites within the complex are aligned along a series of well-defined distributary channel systems with at least four such systems being present within the seismic data. Individual injectites have diameters of c. 1km (approximately the same width as the original depositional channel bodies) with heights of up to 200m; individual injectites show overburden jack-up of up to 60m but are truncated by a major unconformity which connects down-dip into a series of submarine canyons systems which feed a series of basin floor fans.

The distal complex is located at a present-day depth of approximately 3250mbsl (water depth of 1800m). Unlike the proximal complex the injectites in this area do not show any relationship to pre-existing deposits (i.e. channel bodies) and appear randomly distributed as clusters along the upper slope area. Individual injectites have diameters of c. 1km (similar dimensions to the proximal complex) with heights up to 300m and are commonly nested or multi-walled; individual injectites show overburden jack-up of up to 300m and like the proximal complex, the injectites are truncated by the same major unconformity. In this setting the unconformity contains, in addition to submarine canyons, numerous pockmarks and (contourite) scours with localised ponding. An additional complexity in the more distal complex is the presence of a regional crosscutting reflector which cuts through surrounding stratigraphy but is *uplifted* by the injection features: this surface is interpreted as an Opal A/CT transition surface and is also truncated by the overlying regional unconformity in downdip regions.

The relationship between the sand injectite complexes, the Opal A/CT boundary and regional unconformity provides information relevant to the genesis of the injectite complexes. The geometry and distribution of the injectites suggest they formed 'in-situ' i.e. overpressure was *locally* sourced and the parent sand beds are located immediately beneath, and likely attached, to the sand injectites and *not* sourced from deeper horizons. The triggering and driving mechanism may be localised overpressure created by dewatering around the opal A/CT transformation. The regional unconformity post-dates injectite formation and is related to Andean tectonic uplift; the presence of major canyons and associated basin floor fans suggest a period of hinterland uplift and increased sediment delivery across the margin. The overpressure depth was likely relatively shallow (c.500m below the palaeo-seabed) based on maximum thicknesses between the *base* of the injectites, the surrounding stratigraphy and the overlying unconformity.

NOTES:

Kombat Copper Mine; New Thoughts on an Old Deposit

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Kombat Mine is located in the Otavi Mountainland, Namibia, on the northern edge of the Otavi Syncline, just north of the Khorixas-Gaseneirob Fault Zone. The geology of the Otavi Mountainland consists of a lower carbonate-dominated sequence, the Otavi Group overlain by an upper siliciclastic sequence, the Mulden Group, which have been folded into a series of E-W striking doubly plunging synclines and anticlines with wavelengths of around 20km. Based upon this and previous work done in the area the following model for the formation and evolution of the Kombat orebodies is proposed:

- Initially rifting and opening of the Damara aulacogen occurred with the Khorixas-Gaseneirob Fault forming the major northern basin-shelf margin rift fault. This faulting was followed by the accumulation of the Otavi Group comprising deep water carbonate muds to the south of the Fault, a southward facing carbonate ramp sequence with oolite shoals and stromatolite reefs on the rift shoulder and a restricted, evaporite-dominated shelf-lagoon (sabkha) platform sequence to the north of the Fault. Basin collapse then occurred with the rapid deepening of the basin and the accumulation of the carbonaceous, shale dominated distal turbidite Mulden sequence in a deep marine environment.

- Closure (inversion) of the Damara aulacogen then occurred with north-south compression and initially thin-skinned deformation marked by the formation of low-angle thrusting, and associated folding (fold-thrusts or “rolls”) next to the basin margin rift faults. Further north-south compression and subsequent thick-skinned basin deformation was marked by large amplitude E-W striking folding such as the Otavi Valley Syncline, which rotated the previously low angle fold-thrusts to dip +60° S on the northern limb of the Syncline.

- As the Mulden carbonaceous shales passed through the oil window they released hydrocarbons then CO2 and CH4 which migrated into the basin along faults and thrust planes. Release of both CO2 and CH4 from the Mulden converted the Otavi Group anhydrite into calcite releasing the SO4 into the brines, which also migrated along the basin margin faults and thrusts picking up base metals (from the Askevold volcanics?) along the way. The CO2 and SO4 reacted with downward migrating oxidizing groundwater producing carbonic and sulphuric acids that ate their way up through the last four hundred metres of now rotated fold-thrust fracture systems in the Otavi Group forming a hypogene karst cave system (Cf. The Mammoth Cave system).

- Any as yet unconsolidated sands were forced up into the same fracture/karst systems by earthquakes and/or deep-seated intrusions forming injectites (“intrusive sands” or “pseudo-aplites”). These injectites were prevented from migrating upwards by the impermeable shale cap and spread out laterally on the Otavi/Mulden contact forming sand laccoliths. These injectites also formed a porous and permeable migration route for base metal bearing hydrothermal fluids. The Mulden shales (and a silicified cap?) acted as a sealpreventing the further migration of the base metal bearing brines and precipitating their base metal sulphides there by reduction.

- Migration of strongly oxidizing manganese and iron-bearing metasomatic fluids (IOCG or carbonatite-derived?) up the fracture systems produced the Mn-Fe bodies and locally converted the copper sulphides to native copper. Continued N-S compression resulted in the tight isoclinal folding of the rocks at the contact between the Huttenberg and the Mulden and formed a zone of augen mylonite near the dolomite/shale contact (the so-called Transposition Zone). Late E-W compression produced the NE-SW dextral shearing on the cross faults and the sinistral shearing on the Huttenberg-Mulden contact together with the north-south striking cross folding.

- All this was followed by erosion, surface exposure of the carbonates and at least two periods of supergene karst resulting in the conversion of the chalcopyrite and bornite to malachite-azurite. The timing of the silicification is difficult to pin down as base-metal silicate minerals occur suggesting that it came after the main phase of mineralization.

- Why is this change of model important? Because hypogene karst systems generally open downward and occur only be along the fold-thrusts.

- Other comparable copper orebodies are thought to be those found at Tsumeb in Namibia, at Ecton in the UK and the Redstone deposit in Canada.

Thanks go to Bill Nielsen of Kombat Copper for permission to present this paper.

NOTES:

The Miocene-age Frimmersdorf Seam, Lower Rhine Basin: 3D evaluation of a lignite seam and related sand bodies, fractures and fault systems (Garzweiler open-cast mine, NW Germany)

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The Cenozoic-age Lower Rhine Embayment is an extended rift basin located at the NW end of the European Cenozoic Rift System. Rift activity, which commenced in early Oligocene times and was concentrated along NW-SE trending fault systems, was followed by a subsidence phase (up to 1300 m) in parts of the basin. In Miocene times, climatic conditions and the ongoing basin subsidence resulted in the accumulation of thick (up to 100 m) lignite seams, which are currently worked in three active open-cast mines run by RWE Power AG. In the Garzweiler open-cast mine the occurrence and distribution of sand bodies in the c. 14 m thick Frimmersdorf Seam, complicates mining. Initial classification of these highly variable sand bodies suggested complex depositional and post-depositional settings, including the activity of several syn- and post-depositional emplacement mechanisms.

In Langhian times, the extensive coastal mires within the Lower Rhine Basin, as well as the adjacent Rhenish Massif, were drained by several small river systems. The interaction in the coastal mires of the North Sea wave, winds and tides with these fluvial systems, led to the deposition of sand bodies in an extended estuarine depositional setting. However, these syn-depositional sand bodies form only part of the entire sand deposits in the Frimmersdorf Seam. Sand sills and dykes, as well as irregular sand bodies, all of which lack any primary sedimentary structures, have been interpreted in terms of post-depositional soft sediment deformation and sand injection.

Fieldwork within the constantly advancing Garzweiler open-cast mine has provided an excellent database on the sand bodies and their orientations within the lignite. Analysis of the sand injectite orientations has shown a clear relationship with the fracture and fault systems in this part of the Lower Rhine Basin. However, due to the outcrop situation and ongoing mining, a 3D reconstruction of the sand-lignite deposits is difficult. Therefore, a three-dimensional model of the seam, including the field data, highly detailed laser scans, and the fault systems in the area of the Garzweiler open-cast mine has been developed. This model will improve our understanding of the occurrence of sand bodies within the Frimmersdorf Seam, their interrelationship to the local fault systems, and possibly the time frame of sand emplacement.

NOTES:

Poster Presentation Abstracts

Sand injectites and polygonal faults in the northern North Sea

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Cretaceous and Tertiary intervals in the northern North Sea are dominated by fine-grained, smectitic and diatomaceous-rich mudstones. These thick-bedded, mudstone sequences are extensively deformed by numerous large-scale sand injectites and polygonal faults as evidenced on high-resolution, 3D seismic and well data. These sand injectites have been interpreted from multiple intervals in the area (Fig. 1). Both products are commonly attributed to soft-sediment remobilization and fluid flow processes and have been widely documented in the North Sea and nearby basins such as Faroe-Shetland Basin, Norwegian-Danish Basin and Barent Sea. Although sand injectites and polygonal faults in these regions are known to co-exist, some studies have concluded that polygonal faults exert control on sand injectites geometry. Result presented here based on quantitative analysis of both products reveal otherwise.

Quantitative analysis (Fig. 1) for sand injectites in the northern North Sea reveal their dip; width and height values are comparable with other published examples from the North Sea and Faroe-Shetland basins (mean values include 20 - 25°, 995 – 1050 m, 135 – 170 m for dip, width and height, respectively). The polygonal faults, formed in two tiers have average dip of 46° and 36° for the upper and lower tier respectively.

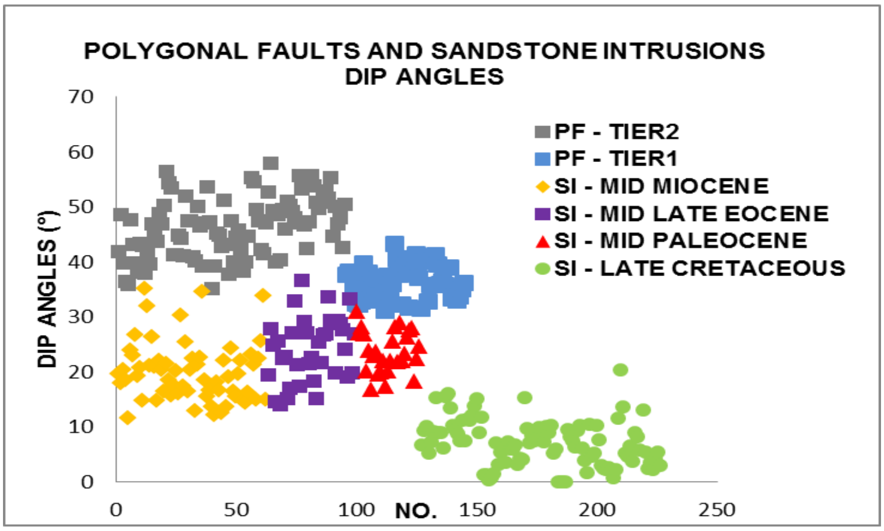

Figure 1 Dip populations of sand injectites and polygonal faults in the northern North Sea (O.Olobayo, PhD Thesis, 2014)

The polygonal faults and sand injectites have different dip populations, which could suggest an independent formation and that the polygonal faults do not exert control on sand injectites geometry. The mudstones have also undergone silica diagenetic transformation evidenced from an opal A to opal CT boundary observed in the area, although no longer active. The sand injectites in the northern North Sea are thought to have been formed during multiple periods of emplacements through time.

Quantitative analysis reveals their dip; width and height values are comparable with other published examples from the North Sea and Faroe-Shetland basins (mean values include 20 - 25°, 995 – 1050 m, 135 – 170 m for dip, width and height, respectively) but much lower for the deeper Cretaceous ones. Polygonal faults deform these intrusion-emplaced, mudstone-rich successions forming two main tiers, such that average dip measured are 46° and 36° for the upper and lower tier respectively. The polygonal faults and sandstone intrusions have different dip populations, which could suggest they formed independently. Difference in dip angles of the Cenozoic and Tertiary intrusions and the upper and lower polygonal fault tiers could be due to original difference in dips during emplacement, compaction from subsequent deposition or variation in mineralogical properties of the mudstone-dominated host rock. Silica diagenetic transformation occurred in the basin with its present day location directly below the Oligocene-emplaced intrusions suggesting a possible genetic relationship. The opal A to opal CT boundary in the area is no longer active.

. The conical and saucer-shaped injectites Soft-sediment remobilization, injection and fluid flow processes and their products such as sand injectites, mud volcanoes, pipes and pockmarks constitute a key, but under-appreciated component of sedimentary basins. Recent advances in subsurface imaging using high-resolution 3D seismic data, integrated with well data, geochemical data and outcrop data have greatly improved the understanding of these soft-sediment remobilization and fluid flow processes in sedimentary basins. The structures provide evidence of focused fluid pathways bypassing the stratigraphic and structural framework and thereby influencing sediment and fluid distributions in the subsurface. This paper presents substantial new results from the description, analysis and interpretation of large-scale sand injectites based on all available data from the Northern North Sea.

The studied intervals, which encompass the entire Cenozoic and Cretaceous succession, have undergone repeated, large-scale remobilization and injection of unconsolidated sand through time. The North Sea is the archetype Giant Injected Sand Province (GISP) with kilometre- scale sandstone intrusions observed within multiple stratigraphic intervals, but this is the first time the northern North Sea has been systematically studied on a regional scale. Well-documented, seismic-scale sandstone intrusions from the South Viking Graben, Outer Moray Firth, Faroe-Shetland Basin, Barent Sea and Norwegian-Danish Basin revealed emplacement during one or two episodes. However, the NNS show evidence for multiple (up to five) major episodes of emplacement. These sandstones, believed to be sourced from different stratigraphic levels, have intruded thick polygonally-faulted, diatomaceous and smectite-rich mudstones; probably facilitated by hydrocarbons and diagenetically-released water in spatio-temporally varying proportions.

These remobilized and injected sands thus have numerous implications for hydrocarbon exploration and production; and therefore be incorporated into present stratigraphic frameworks and reservoir models.

Sandstone intrusions in fractured crystalline basement: implications for hydrocarbon reservoir connectivity

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Economically viable hydrocarbon reservoirs in fractured/faulted crystalline basements are known in locations throughout the world, including Canada, China, Vietnam, India and United Kingdom. Most of the crystalline rock reservoirs underlie a regional nonconformity upon rock that underwent prolonged weathering, causing *in situ* replacement of feldspar and mica by clays, and/or accumulation of clay within fractures; a zone of dilatant fractures exists deeper in the crystalline rock volume.

Necessary conditions for a hydrocarbon reservoir in fractured crystalline basement rock are: i) presence of an interconnected, open network of faults and fractures, ii) a seal provided by caprock of impermeable weathered material derived from basement or by younger sediments which directly overlie the basement, and iii) hydrocarbon sources. Injected sediment within fractures may act as a natural ‘proppant’ that creates open pathways for fluid migration or residence, a prospect that can be best evaluated through study of surface exposures of basement-hosted sedimentary injectites. Basement-hosted injectites, as reported in published literature, occur in all tectonic environments, including extensional settings in Proterozoic host rocks of Sweden and Denmark, and granites of Sinai Peninsula, Egypt; transcurrent deformation in Colorado and NW Scotland; and in the contractional realm in Sicily and Calabria. In the subsurface in modern settings, extensive injectite systems are certain to exist at sites of sand eruptions induced by seismicity and in subglacial bedrock subjected to fluid overpressure beneath ice sheets. This contribution reports on two regional-scale crystalline-rock-hosted sedimentary injectite systems that offer a direct means to investigate fracture geometry, abundance, aperture and spacing, parameters that have bearing on porosity and permeability characteristics of crystalline basement.

Neoproterozoic injectites in Colorado form a continuous system >70 km in length, consisting of km^{3}s-scale parent bodies and dykes with apertures of 1 mm to 7 m. They are vestiges of a system that covered a minimum area of 24 000 km^2. Parent bodies and injectites consist of granule- to cobble-sized quartz clasts suspended within a matrix of rounded, unsorted medium-fine to fine quartz sand; characteristics that provide evidence of sediment fluidization and remobilization. The majority of dykes strike NNW-SSE, with steep dips, parallel to a pervasive fracture array within the crystalline host rocks. In one locale, dykes (0.1 to 0.4m thick) injected into normal fault planes and relays can be traced

Figure 1. Annotated outcrop photo of Neoproterozoic quartzose sedimentary injectites within 1.03 Ga Pikes Peak Granite, Colorado Front Range, USA. The exposure is near the northern limit of a laterally continuous system of fault-bounded parent sandstone bodies and associated dykes. Despite the over-print of brittle deformation from Phanerozoic events, primary relationships are locally well preserved.

laterally for 600m. Anisotropy of magnetic susceptibility data for nine sites

yielded subhorizontal AMS ellipsoids indicating lateral injection. In many areas, the purple-red, hematite-cemented sandstones show pervasive discoloration, mottling, and fracture-parallel bands of bleaching, that are a consequence of circulation of reducing fluids. A chemical characterization of the fluids that migrated through the permeable sandstones has yet to be completed.

Injectites of probable Plio-Pleistocene age in Calabria, Italy, are found within coastal exposures of coarse-grained tonalite. At one site bordering the Tyhrennian Sea, dykes 1mm to 20cm thick consist of micritic carbonate containing tonalite fragments and igneous grains. At a second location bordering the Ionian Sea, injected material is quartz sand, within dykes that are 1mm to 1m thick. Small dykes occupy pre-existing NW-SE conjugate fractures at 1- to 2-meter spacing, in the footwall of a low-angle reverse fault. Injected material surrounds angular fragments displaced from dike margins. A thicker dike borders a moderately dipping normal fault that dropped ?Pliocene sediments down against early Permian tonalite. The dike can be traced into a lower volume of sediment disrupted by fluidisation. Continuous for >5m, the dike passes out of the sediment into a tonalite host.

The aim of our ongoing research at these sites, involving characterization and structural analysis of the sandstone intrusions and fractured crystalline host rock, is to illuminate shallow crustal processes that lead to formation of secondary porosity generated through fracturing, identify unconventional fluid migration pathways, and determine the role of transient fracture permeability. Our initial results suggest that sand injections serve to open faults and fractures and thus play an important role as fluid and hydrocarbon migration pathways in crystalline rocks. Regionally extensive injectite networks in crystalline rock are probably more widespread than is presently known.

Figure 2. Photographs of tonalite-hosted injectite features that indicate high energy deposition, Pietragrande, Calabria, Italy. a) varied geometry of planes injected by sand, indicative of hydraulic fracture. b) Flutes upon dike margin, with grain size variations providing an indication of fluctuating transport energy. The flutes would provide a emplacement direction, had the tonalite block been in place. c) Sandstone dike containing fragments of host rock ripped from the dyke margin. There is complementarity of angular edge shapes among fragments, and between fragments and wall. The features in a-c are indicative of sand fluidization and the injection of sediment by overpressured water into pre-existing tectonic structures.

Architectural Organization and Petrography of Tumey Giant Injection Complex, California (USA)

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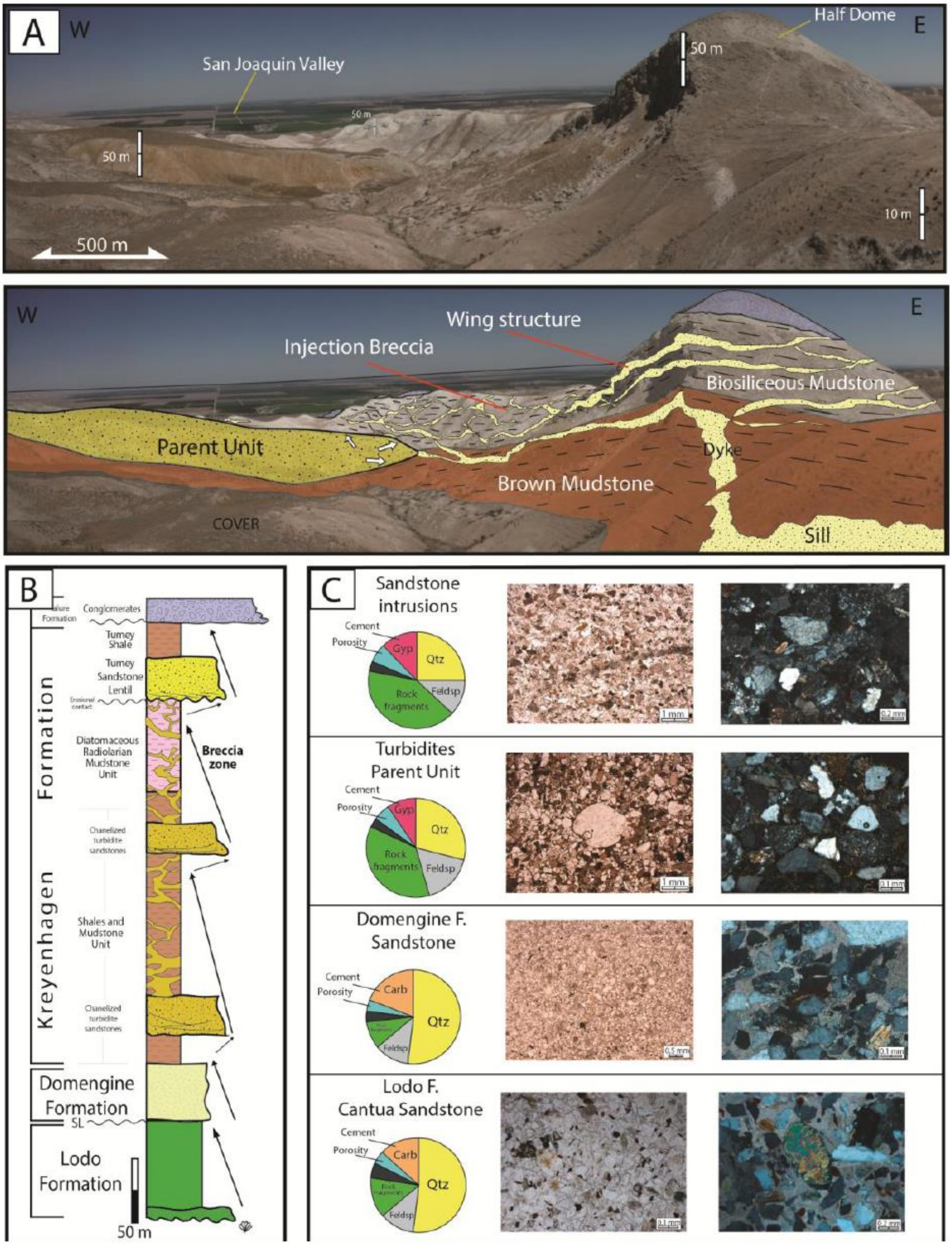
Giant sand Injection complexes besides being special and intriguing geological phenomena play a very important role in the evolution of sedimentary basins and as hydrocarbon-bearing sandstone intrusion reservoirs. They are typified by evidence of sand fluidization and injection in the shallow crust and are recognized extensively in outcrops and in the subsurface. Detailed geological mapping supported by stratigraphic, structural and petrographic analysis allow the understanding of the relationships between depositional sandstone (parent units), sandstone intrusions (sills, dykes, saucer-shaped intrusions) and hydraulically-fractured host mudstone. Their mutual relationships studies at outcrop strongly support exploration for and development of hydrocarbon-bearing sandstone intrusions.

The Tumey Giant Injection Complex (TGIC) intrudes a mudstone interval of deep marine Kreyenhagen Formation (Eocene) in Central California. In order to better characterize this complex a key area localized in Tumey Hill has been analysed. Here the TIGC has a lateral extension of over two kilometers and cut the stratigraphy at least for 400 meters thick. In this area the Kreyenhagen Formation consists of thin-bedded brown mudstone that grades upward into very-pale biosiliceous mudstone that alternates with levels of channelized gray, lithic, turbiditic sandstones (Figs. A and B). Mudstone is intensely fractured and contains sandstone intrusions with similar mineralogy to the turbidites. This sequence unconformably lies below the Tumey Sandstone Lentil which cut the biosiliceous mudstones and the sandstone intrusions constraining the sand injection complex event to the Eocene.

The TGIC comprises different architectural elements: (1) host hydraulically-fractured mudstone, (2) depositional, partially remobilized, lithic sandstone (parent units), (3) an interconnected network of sandstone intrusions and, (4) injection breccia, which is particularly well-developed in the contact of biosiliceous and brown mudstones. Parent units consist of amalgamated channelized gray, fine to medium grained lithic sandstone in which primary sedimentary structures are preserved and commonly have mudstone clast and conglomeratic basal lags. Parent sandstone is extensively modified by liquefaction and fluidization processes that were promoted by fluid overpressure; the upper parts of the parent units are typically structureless. The intrusive network comprises near to bedding-parallel sill and saucer-shaped intrusions and bedding-discordant dykes that are emplaced in a NW-SE oriented fracture system constrained by NE-SW stresses. The injection network has a wide range of intrusion geometries including multi-layered sills, stepped dykes and saucer-shaped intrusions often with spectacular wing structures mainly oriented toward SW. These injection breccia zones are concentrated around the parent units, especially developed in the biosiliceous strata. This breccias consist of a variety of structures and textures with biosiliceous mudstone clasts with angular and rounded shapes and range from milimetric to metric scale diameters. The petrography of depositional and injected sandstone reveal strong compositional and provenance similarities (Fig. C). Both are lithic sandstone cemented by gypsum with very similar detritic composition and with a provenance signature typical of a recycled orogen. They strongly differ from the sandstones recognized in the underlying formations which have a completely distinct mineral assemblage and a provenance signature from a dissected magmatic arc. Mineralogical data confirm that the TGIC parent units are the turbiditic sandstone in the Kreyenhagen Formation.

The TGIC is a good example of a giant sand injection complex that is intruded into highly fractured host mudstone and has produced a wide range of structures and geometries that are valuable analogues to support subsurface analysis of similar formations.



***Figures**: Geological and petrographic features of the Tumey Giant Injection Complex. **A)** Panorama view of the Tumey Hills area (above) and the the respective geological interpretation (below) with the sandstones intrusion net represented in whitish yellow. **B)** Stratigraphic column of the Tumey Hills. **C)** Petrographic thin sections of different sandstone units and the respective quantitative analysis (pie charts) of detritic composition, cements and porosity.*

Spatial and Genetic Relationships between the Fluidisation and Injection of Eolian Sand and Volcanic Processes, Torres, Brazil

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The interaction between aeolian sand of the Botucatu Formation (Jurassic-Cretaceous), basaltic magmatism of the Paraná Volcanic Province (Cretaceous) and a heated giant aquifer system (Guarani aquifer) generated an excellent example of intrusive sand injection into volcanic rock that form large exposures on the coast of the city of Torres (Brazil) and adjacent areas.

The heated, overpressured fluids hydraulically fractured the overlying volcanic rocks and formed an injection complex of sand injection breccias, sills, dykes and extrudites. Outcrop mapping and the petrographic analysis of the sandstone intrusions and volcanic hosts allows us to characterize the geometry, composition and textures of this sand injection complex by producing a series of geological cross sections that characterise macro- and micro-features.

The volcanic extrusions that covered the aeolian dunes contributed to the increasing of the lithostatic pressure on the dunes, acted as seals to the escape of fluids and, as a source of heat that raised the regional temperature of the groundwater (a hydrothermal source). Consequently, the generation of fluid overpressure reached a point where the hydraulic pressure exceeded the lithostatic pressure, causing the hydraulic failure of the volcanic cover thereby causing widespread brecciation and promoting the fluidization, remobilization, and injection of aeolian sand from the underlying Botucatu Formation. The complex is composed of (i) aeolian sandstone parent units, which were fluidized and injected into, (ii) injection breccia zones with clasts (0.5 - 50 cm diameter) of angular volcanic fragments that are often cut by <0.1 cm thick sandstone dykes , (iii) a network of sandstone dykes above the breccia zones, and (iv) sandstone extrudites.

The injection breccia is typically developed in the amygdaloidal crusts of the two overlying mafic volcanic lava flows. The two brecciated intervals (breccia level 1 and 2) have stepped and crudely wing-like geometry (3-10 m thick). The lower brecciated interval (breccia level 1) is at least 1 km wide and 3-10 m thick and has in some portions a sharp upward transition into a structureless, fine- to medium-grained sandstone (0.5-1 m thick and 100 m wide) with sub-parallel banding near the upper margin. Within the brecciated intervals irregular pockets of sand-supported breccia occur suggesting that the suspension of the clasts into the overpressured fluidized sand was in a turbulent flow. Silica-cemented sandstone dykes (0.1 - 30 cm thick) propagate above the sill emplaced into a network of lozenge and staggered fractures in the overlying andesitic rocks. These relationships associated with the lack of evidence of high temperature interaction (>1150°C) indicate that the sand injection occurred after the cooling of the lava flows. Later igneous dykes and sills cut the sand injection complex and its volcanic host rocks and are evidence of intense and continuous magmatism that occurred during and after the sand injection event.

Mapping of sandstone intrusions and their relationships with Cretaceous magmatism in Torres allows an enhanced understanding of the genetic and structural relationships of sand injection complexes in volcanically active environments associated with hydrothermal processes. This occurrence can be used as an example of hydrothermal-sand-injection complex related to igneous activity in similar less well-exposed geological environments.

KEY WORDS: sand injection complex, magmatism, hydraulic fracture, injection breccia, Cretaceous

Sand injection and polygonal faulting in the Great South Basin, New Zealand

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Subsurface sediment remobilization phenomena including soft sediment deformation, sand injection and mud volcanism have been recognized to play a significant role in petroleum exploration. Wing-shaped seismic-scale anomalies interpreted as sand injectites based on their similarities with North Sea examples have been identified in lower Paleocene sediments of the Great South Basin, New Zealand. The structures are evidenced on the 3D seismic data at about 1,700 ms TWT (two-way traveltime) beneath the seabed. The sand injectites occur below a well-developed polygonal fault system within Paleocene to Eocene sediments which comprise siliciclastic sediments from the Kawau Formation overlain by mud dominated sediments of the Laing Formation. The wing-shaped sand injectites are usually located near the downward extent of polygonal fault tips possibly implying a genetic link. It is thus possible that the sand remobilization and injection process may relate to polygonal fault formation, either responding to the fault nucleation or affecting it, or that both are a response to a common trigger, e.g. dewatering. This is the first time that seismic-scale sand injections and their link with polygonal faults have been described from the Great South Basin. The study adds to an emerging realization that sand injectites occur in many deepwater basins with possible implications for basin evolution and hydrocarbon exploration.

3D Characterisation and Modelling of Sandstone Intrusions

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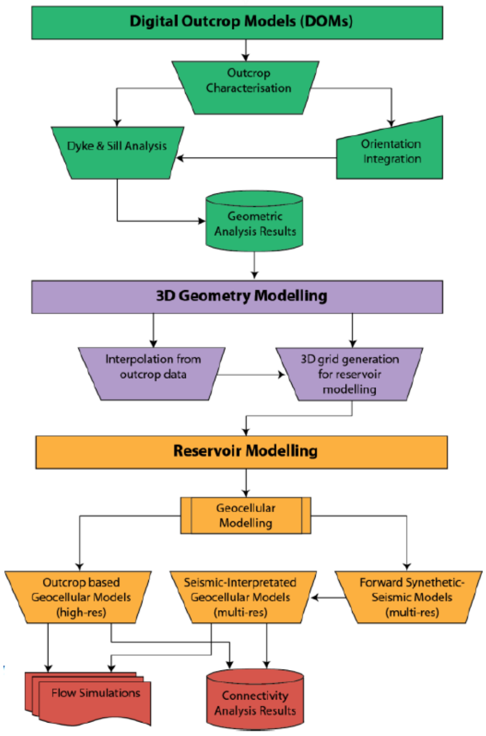
Key words: *sandstone intrusions, outcrop, deterministic, reservoir modelling*

Sandstone intrusions are recognised in many petroleum systems and on the UKCS constitute major reserve volumes in some of the largest fields currently under development (Krakken, EnQuest; Catcher, Premier; Mariner, Statoil) and are a vital component of small pool in-field and near-field exploration. Because sandstone intrusions are discordant to bedding and have complex geometry they are challenging to image using seismic data and typically their presence has led to underestimation of reserves in both large (Alba, Gryphon, Harding) and small (Chestnut, Brimmond) fields. Typically operators estimate 15-40% of reserves cannot be imaged using seismic data and an important positive factor common to sandstone intrusions is their excellent connectivity that gives them high vertical and lateral transmissibility and Kv typically very similar to Kh.

Development of sandstone intrusion reservoirs is becoming inextricably associated with the implementation of deep-resistivity logging while drilling as an aid to geo-steering. Our experience working with several research sponsors is that using outcrop analogue data during well planning has greatly improved the interpretational value of deep resistivity tools during drilling. Central to this is the capture of the range and variety of sandstone geometries that are encountered and expected in different parts of sand injection complexes. Outcrop data are thus used routinely to constrain drilling risk, in particular, they have allowed quantitative determination of the genetic relationship of “wing-like” intrusions to parent depositional bodies and associated dykes and sills. However, even with the successful application of outcrop analogues, the current toolset available within reservoir modelling packages cannot capture the geometry present. This uncertainty prohibits reservoir modellers and geologists from accurately predicting reservoir geometry and behaviour.

To mitigate these challenges we propose a multivariate modelling approach and a subsequent deterministic analytical approach that use commercial and University developed software, to create more accurate 3D models of sandstone intrusion geometry and architecture (Figure 1). The proposed methodology will use existing quantitative and spatially accurate outcrop analogue data to produce multiple realisations of reservoir models and simulations. Recent adaption of quantitative 3D surveying techniques, such as lidar and photogrammetry, are valuable assets when constructing and developing reservoir models. The methods are currently applied to outcrops of the Panoche Giant Injection Complex and Tumey Giant Injection Complex, central California from which a large database of spatially accurate 3D information is available. In turn this is used to generate digital outcrop models (DOMs). When the DOMs are fully realised, high-resolution (5 cm – 10 cm) geostatistical information for the associated features is extracted and used to constrain depositional and reservoir models.

Ultimately, this information will help to improve hydrocarbon recoverability and will allow better constrained pre-drill reserve prediction.



The proposed workflow integrating data from subsurface, outcrop and forward seismic models.

Burlington House
Fire Safety Information

If you hear the Alarm

Alarm Bells are situated throughout the building and will ring continuously for an evacuation. Do not stop to collect your personal belongings.
Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshall on that floor.

Fire Exits from the Geological Society Conference Rooms

Lower Library:
Exit via Piccadilly entrance or main reception entrance.
Lecture Theatre
Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the main reception entrance.
Piccadilly Entrance
Straight out door and walk around to the Courtyard or via the main reception entrance.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS**.

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society.

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First Aid

All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities

The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.

Ground Floor Plan of the Geological Society, Burlington House, Piccadilly