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The Sedimentology of High Perm Streaks and Reservoir Heterogeneity: Implications for CCS

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ABSTRACT

The impact of high perm streaks and reservoir heterogeneity on oil and gas production and associated enhanced oil recovery (EOR) techniques is readily appreciated, but less attention has been paid to the importance of these attributes in relation to carbon sequestration (CCS). Heterogeneities may include more permeable sandstone or limestone beds, permeability enhancement through diagenesis and structural overprints such as fracturing and cataclasis. Other factors serve to degrade reservoir quality, in particular diagenetic cementation.

An understanding of reservoir sedimentology and its impact on high perm streaks in both the horizontal and vertical plane is critical to the successful modeling of carbon dioxide injection and sequestration. Depositional settings ranging from fluvial, aeolian, lacustrine, coastal, shallow to deep marine environments in clastic settings are examined below in terms of their potential to incorporate significant and predictable high perm streaks and reservoir heterogeneities that could impact CCS. Many of these sedimentary features correlate to previously identified thief zones in producing hydrocarbon fields, but a full overview of the associated risks, as they relate to CCS, has not previously been compiled.

INTRODUCTION

More than 400 CCS projects have been initiated around the world, including everything from short-lived pilot projects to ongoing, large scale operations sequestering millions of tonnes of CO_2 annually. As an example, at least twenty-six CCS projects are currently in progress in Alberta, Canada. Many of these projects are in contiguous acreage, using the same target reservoir interval, and this has the potential to lead to leakage of injected fluids from one project site into another.

While structural features such as faults and fractures have the greatest potential for the uncontrolled passage of fluids, high perm streaks and reservoir heterogeneity can also contribute to interference or even the catastrophic escape of carbon dioxide to the surface. A natural limnic eruption at Lake Nyos, North Cameroon killed 1746 people, due to a sudden release to surface of CO_2, and a breach in seal rocks or the escape of injected superfluid through a high perm streak in a CCS project could be equally catastrophic. For this reason, an in depth understanding of the risks associated with sedimentological heterogeneities is critical when planning carbon sequestration. Different depositional settings pose different challenges, while the impact of lateral and vertical changes in diagenetic cementation can lead to injectivity issues that may limit sequestration levels.

In this paper, the challenges associated with fluvial to open marine clastic settings are examined and used to rank reservoirs in terms of their suitability for carbon sequestration. This ranking can be combined with other requirements for successful injection (depth of burial; presence of seal or ideally seals; quiescent tectonic setting, etc.) to determine the most suitable injection targets. Examples drawn from ongoing CCS projects around the globe are utilized to demonstrate where reservoirs have performed as expected, and also where problems with reservoir heterogeneity have been encountered.

TABLE 1 Reasons for variations in permability

Factor	Reduction	Enhancement
Structural	• Sealing faults and mud dykes • Juxtaposition	• Fractures • Open faults
Sedimentary	• Shale baffles • Shale barriers • Evaporites (creep) • Igneous seals • Heterogeneity in reservoir properties	• Channel sands • Sand sheets • Homogeneous sandstone or limestone
Diagenesis	• Cementation • Replacement	• Dissolution • Replacement
Pressure	• High pressure cells	• Low pressure zones

SOME FACTORS LEADING TO VARIATIONS IN PERMEABILITY

Both horizontal and vertical permeability can be enhanced, for example due to the deposition of porous sedimentary rocks. Ideal reservoirs for injectivity include channel sands and sand sheets, particularly when the sandstone is relatively homogeneous. Limestone can also provide excellent reservoirs. Dissolution or replacement can also open up additional pore space, while biogenic features such as roots and burrows can also provide conduits (Table 1).

However, the opposite is also true. Many sedimentary features can reduce permeability, such as shale baffles and barriers to flow, for example deltaic clinoforms or inclined heterolithic stratification (IHS) in point bars; evaporites and igneous seals; and basic heterogeneity in reservoir properties, such as the change in composition in deeper, low energy settings. The impact of diagenetic cementation cannot be underestimated, as it can destroy a reservoir. Variations in pressure can also impact reservoir quality.

While this paper focuses on sedimentology, there are a variety of structural features that can directly affect permeability and porosity. These include faults which may be open, leading to leakage, or closed due to cementation, injection of impermeable, mobile sediment or juxtaposition. Fractures can lead to more permeable reservoir rocks and can act as high perm streaks when concentrated in fault zones, particularly thrust sheets or around folds.

DATA PRESENTATION

Each major clastic depositional setting is examined in turn for their suitability for CCS. Factors that would degrade potential reservoirs in terms of high perm streaks or barriers to injectivity are discussed. Examples of existing CCS projects are described, many of which tend to show the pitfalls of incorrect reservoir selection. Table 2 summarizes this data. The associated figures showing the individual depositional settings have red arrows highlighting potential high perm streaks, through which injected CO_2 superfluid could migrate and potentially escape.

TABLE 2 A summary of the different clastic depositional settings in which Carbon Sequestration projects have been undertaken. The table also details the character of the reservoirs and potential associated flow pathways (high perm streaks) and barriers to successful injection. Examples of both successful and failed projects are included. The different depositional settings have been ranked as CCS targets based on their CCS track record.

Depositional setting	Ranking	Pathways to flow	Barriers to injection	Comments	Projects – relative successes	Projects – potential failures
Fluvial lowstand: low sinuosity channels	2	Channels and associated sheet sands Creeks Juxtaposition Clay grain alignment	Mudstone interbeds Palaeosols	Potential flow in all directions through lowstand sheet sand; many pathways Low chance of barriers to flow	• ROAD (Porthos) Project, Rotterdam, sold out, in development in high energy, fluvial reservoir. • Collie SW Hub, Australia, Triassic fluvial ssts	• Moomba Project, Australia, braided fluvial reservoir. Project on track to commence injection in 2024. Current 35% cost overrun. Possible rule breach due to EOR. Diagenetic cements seen in nearby project.
Fluvial Transgressive: isolated channels	9	Channels Creeks Crevasse splays Juxtaposition Clay grain alignment	Mudstone interbeds Oxbow lakes and ponds Palaeosols Overbank muds	Isolated channels in mudstone so few pathways except along channels Low net:gross so less potential storage High chance of barriers to flow	None known associated with CCS	
Fluvial Highstand: meandering channels	6	Lateral accretion surfaces Channels Creeks Crevasse splays Juxtaposition	Inclined heterolithic stratification Oxbow lakes and ponds Overbank muds	Peak flow at channel base and in sandy point bars; juxtaposition likely; extensive point bars and many pathways High chance of barriers to flow only in muddy point bars (IHS)	• Chinese coal bearing reservoirs considered for CCS	• Snohvit Field: Tubaen Fm is deltaic to fluvial. Dominated by channels leading to compartmentalization. Also variable cementation. Many faults create barriers.
Aeolian	8	Ergs; dune fields	Cemented supersurfaces Playa lakes; mud flats; interdune deposits Wadi deposits	Potential for huge dune fields (depending on preservation potential) with many pathways Low chance of barriers to flow in dune fields although interdune deposits may hinder flow. Supersurfaces may act as barriers		• None known: Leman Sst evaluated and did not pass. Too much interaction with lacustrine sediments (Silverpit Fm); transgressive and regressive events, variable fluvial systems
Estuarine	3	Estuarine channels Mouth bars in juxtaposition Contact to upper shoreface Beach and strandplain	Cemented ravinement surfaces Mudstone baffles during small transgressions Mudflats Lagoons	Contact to upper shoreface leads to open pathways. There may also be estuarine channels providing high perm streaks Some chance of baffles and barriers due to periodic mud deposition in mudflats; flocculation and during transgressions	• QUEST: Cambrian estuarine channels act as pathways • Aquistore, SK: Cambrian Deadwood Fm. includes tidal deposits.	• In Salah Gas Storage, Algeria, using Carboniferous estuarine sst, Much lower porosities than modeled. Caprock breach.

Depositional setting	Ranking	Pathways to flow	Barriers to injection	Comments	Projects – relative successes	Projects – potential failures
Deltaic	5	Updip into fluvial channel Across delta and through distributaries Alongshore into shoreface deposits Offshore through submarine canyons	Mudstone baffles during small transgressions and during storms Delta top lagoons Clinoforms	Contact to upper shoreface leads to open pathways. Fluvial and distriubutary channels may be high perm streaks. Offshore through canyons. Chance of baffles and barriers during transgressions. Deltaic clinoforms will probably be barriers. Synsed faulting may form barriers.	• Northern Lights, Norway: Johansen Fm. is deltaic	• Snohvit Field: Tubaen Fm is deltaic to fluvial. Dominated by channels leading to compartmentalization. Variable cementation. Many faults create barriers. Less storage capacity than expected.
Upper Shoreface	1	Updip into fluvial channel or estuarine channel Offshore through canyons or gutter casts Possible turbidites	Mudstone baffles during transgressions and during storms Cemented horizons	Fluvio-estuarine channels may be high perm streaks. Offshore through canyons or gutter casts. Alongshore due to porous sands. High chance of baffles and barriers during transgressions.	• QUEST: Cambrian estuarine channels act as pathways • Aquistore, SK: Cambrian Deadwood Fm. includes tidal deposits • Pathways: Cambrian shoreface BSU • Decatur, USA: Cambrian Mount Simon Sst. • Snohvit Field: Sto Fm. working well.	Core evidence shows that the Basal Cambrian Sandstone is heavily siderite cemented to south of the QUEST Project, with much lower porosities.
Lower Shoreface	7	Gutter casts may act as conduits Laterally extensive storm deposits Flow up dip into upper shoreface sands	Baffles very likely due to mud deposition between storms	Contact to upper shoreface leads to open pathways. Fluvial channels may be high perm streaks. Offshore through submarine canyons. Chance of baffles and barriers during transgressions. Clinoforms.	• Haizume Fm, Pleistocene marine sst, heterolithic facies, used for Nagaoka Storage Project, 2003. • QUEST upper to lower shoreface – successful CCS project.	• Some concern that Haizume Fm sediments may be too heterolithic for successful injection.
Offshore	4	Up dip into shoreface deposits Laterally in sheet turbidites	Offshore mudstones encase targets Turbidite flows often constrained in canyons and channels May have internal baffles	Potential leakage up dip into shoreface deposits. Sheet turbidites will allow lateral flow but likely to still be encased in mudstones. Sleipner shows the potential problems. High chance of baffles and barriers due to mudstone deposition between events		• Sleipner Field, Norway: Utsira Fm. lowstand fans. Vertical leaks through chimneys, very low relief reservoir, shale breached after 3 years, horizontal perm barriers identified • Gorgon Field, Australia. Jurassic turbidites, project racked by technical problems – releasing same amount of CO_2 as saved by rooftop panels country-wide

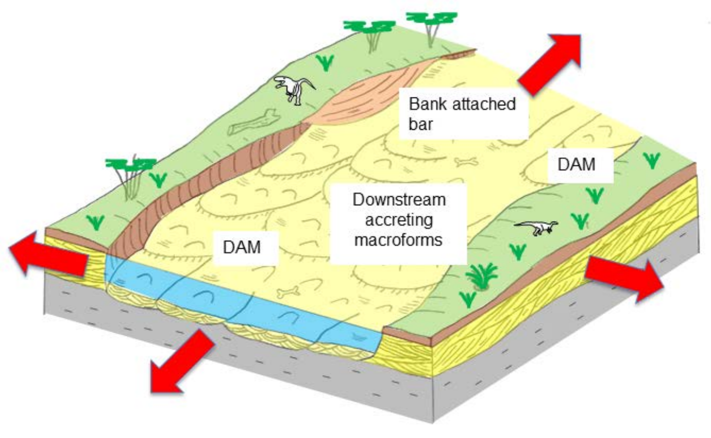


FIG 1A LOW SINUOSITY FLUVIAL RESERVOIRS

Stacked low sinuosity channels from the Campanian Oldman Formation at Ferry Crossing, eastern Alberta

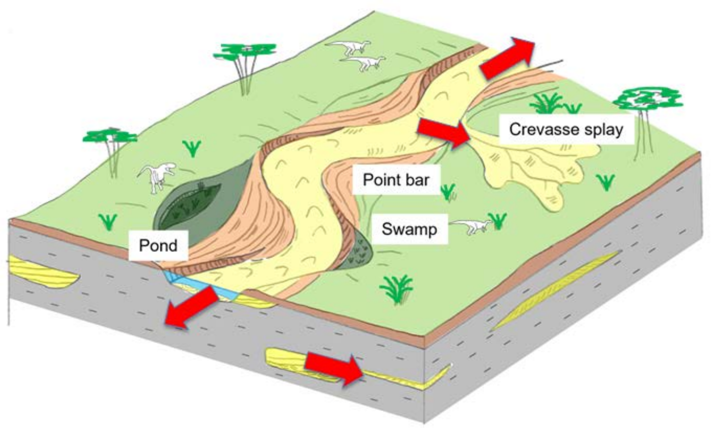


FIG 1B ISOLATED FLUVIAL CHANNELS

Isolated mangrove channels from the Miocene Sandakan Formation, Sabah, Malaysia

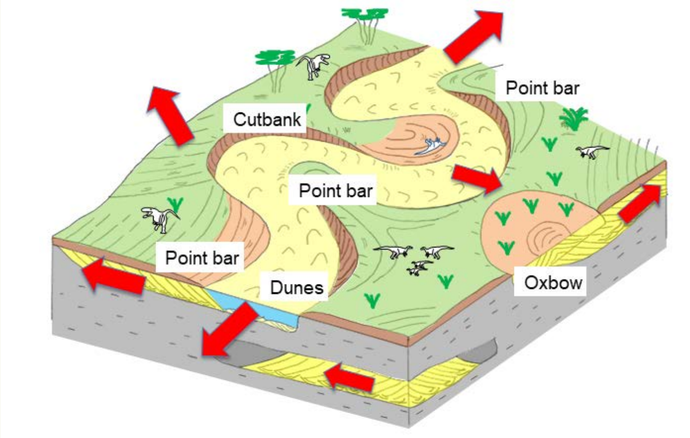


FIG 1C MEANDERING FLUVIAL CHANNELS

Stunning meandering channel with lower trough cross-bedded sand overlain by inclined heterolithic stratification and capped by a mud filled oxbow lake, Dinosaur Park Formation, upper Cretaceous, near Brooks, Alberta

FLUVIAL DEPOSITS

The character of fluvial reservoirs depends to some extent on their sequence stratigraphic context. Put simplistically, relative lowstands are associated with low sinuosity channels, which may even be braided; transgressive deposits feature isolated channels; while highstand deposits are usually dominated by meandering channels.

Lowstand fluvial deposits often form sheet sands, with many permeable pathways through which injected fluids can migrate. Typically, there are few flow barriers with little mud. The Moomba Project is being developed in South Australia, capable of storing 1.7 MMt of CO_2/year (ultimately 20 MMt) in depleted gas reservoirs of Cooper Basin fields. The reservoirs are Jurassic Hutton and Namur braided fluvial sandstones with minor siltstone interbeds and initial tests were good. However the Celsius-1 geothermal well did not produce anticipated flows, probably due to iron oxide cements seen in the Gidgealpa Field.

Transgressive fluvial deposits result in isolated channels in mudstone with few pathways except along the channel axis. No CCS projects are known in these deposits, but isolated channels in Oman's Hazar Field all have different reservoir pressures, showing that they are not in communication. Meandering channels (highstand) deposit sand sheets associated with point bars, often compartmentalized due to mud filled oxbow lakes formed by channel abandonment. This was seen in the Snohvit Field, Norway, where CO_2 has been injected into the Jurassic Tubåen Fm. since 2008. Disappointing storage capacity is due to unexpectedly low porosities encountered in the Tubåen Fm., leading to the drilling of a new site to add storage in the Stø Fm.

AEOLIAN RESERVOIRS

There is the potential to utilize huge sand dominated dune fields, but with a significant chance of fluids migrating laterally through the system. The Leman Sandstone in the UK North Sea was evaluated for CCS and found wanting, due to faults and compartmentalization; problems with low pressures leading to hydrates forming in wells; induced fractures; and mixed continental deposition of aeolian, fluvial and lacustrine environments which interfinger with the saline lake deposits of the Silverpit Formation. Most other UK aeolian reservoirs are overpressured, so not suitable for long term gas injection.

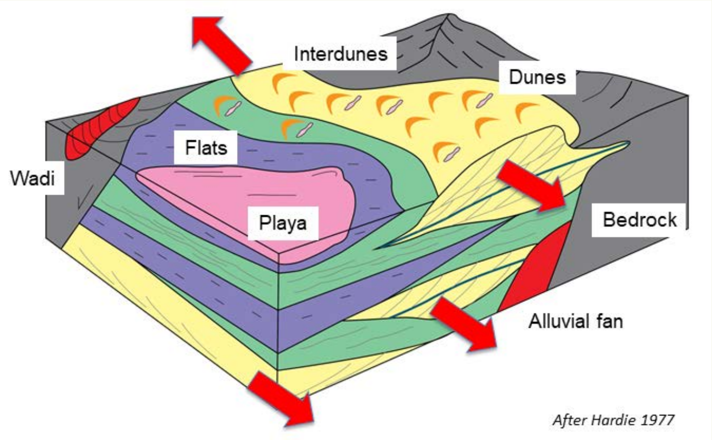


FIG 2 AEOLIAN RESERVOIRS

Stacked aeolian sandstone beds, Triassic, SW of Grand Junction, Colorado

ESTUARINE AND SHOREFACE RESERVOIRS

These reservoirs are usually in contact with shoreface deposits, leading to potential fluid migration. There may also be estuarine channels providing high perm streaks. Interbedded mudstones deposited in mudflats, due to flocculation or during transgressions are common and may form baffles to flow. The successful QUEST CCS Project includes Basal Cambrian Sandstone estuarine and shoreface deposits and has performed well, with anecdotal evidence of high perm streaks in associated tidal channels that have not materially affected the project.

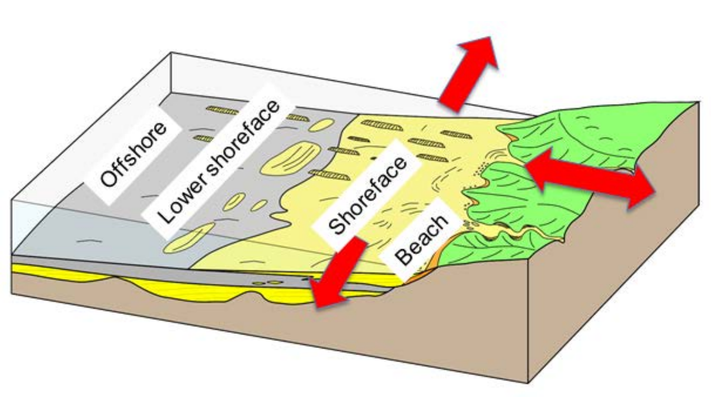


FIG 3A ESTUARINE AND UPPER SHOREFACE RESERVOIRS

Outcropping estuarine fill, Horseshoe Canyon Formation, Drumheller, Alberta

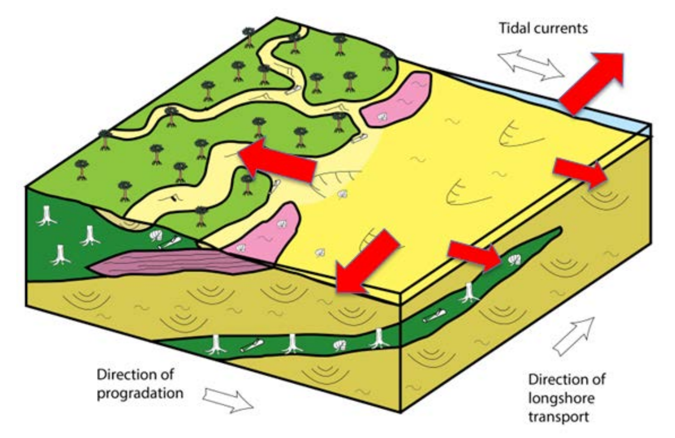
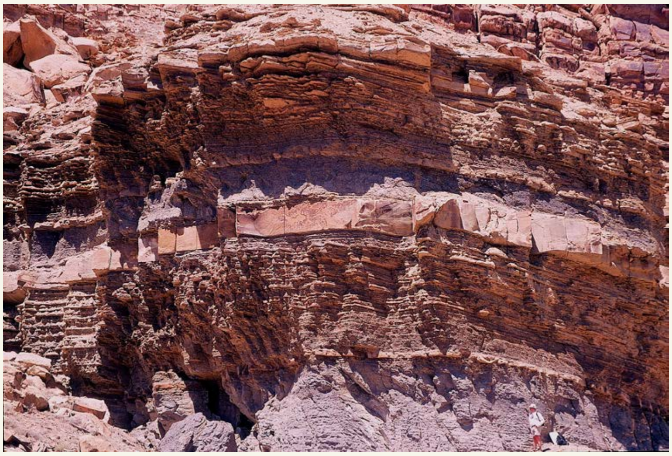


FIG 3B UPPER SHOREFACE RESERVOIRS



Upper shoreface parasequences, Cretaceous Book Cliffs, Utah

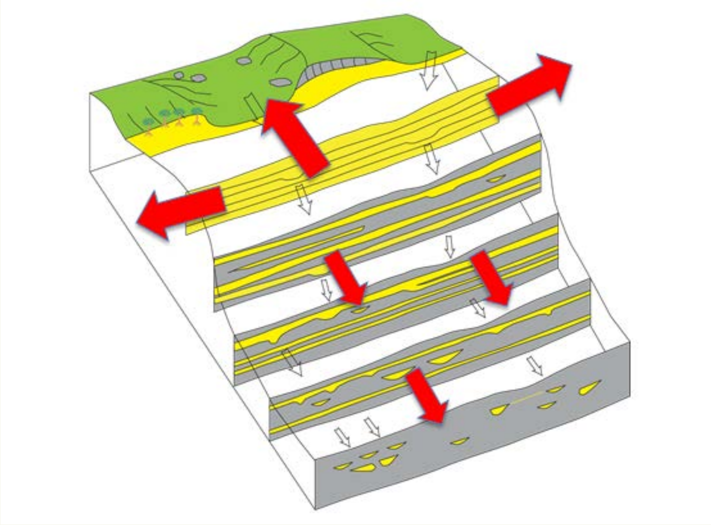


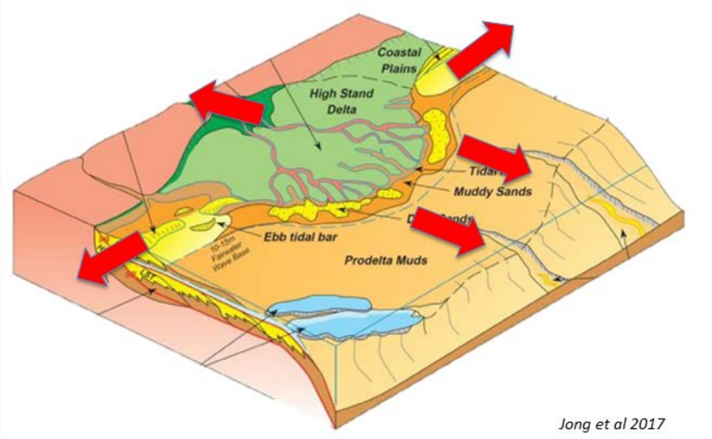
FIG 3C LOWER SHOREFACE RESERVOIRS

Giant, sand filled gutter casts in lower shoreface deposits, Miocene Sandakan Formation, eastern Sabah, Malaysia

The In Salah CCS Project in Algeria utilized Carboniferous, fine-grained, estuarine sandstone. Over 7 years of injection, CO_2 pressure climbed to dangerous levels and the caprock eventually fractured (luckily there was a 950 m thick overburden), so the gas is now vented to the atmosphere. Factors responsible include much lower porosities seen in the reservoir rocks than originally modeled, and a heterogeneous CO_2 plume migrating laterally.

Shoreface deposits like those of the QUEST Project are excellent CCS targets with laterally extensive sandbodies, although fluvio-estuarine channels can form high perm streaks. Other Cambrian examples include the Deadwood Fm. of Saskatchewan and the Mount Simon Sandstone in the US. Despite the success of QUEST, other shoreface deposits, such as the Aptian Avalon Formation in the White Rose Field, Nova Scotia, may have up to 30% of the reservoir cemented due to the dissolution of aragonitic shells.

Lower shoreface settings connect to upper shoreface deposits which may lead to updip migration into laterally extensive sandstones, and there is the potential for leakage into offshore canyons. Mudstone baffles and barriers are common in more distal settings. The heterogeneous Haizume Fm. in Japan was selected for the Nagaoka pilot project, but there are concerns over connectivity due to the numerous siltstone and mudstone baffles.



Jong et al 2017

FIG 4 DELTAIC RESERVOIRS

Prograding Pliocene deltaic deposits, near Sorbas, southeast Spain

DELTAIC DEPOSITS

Deltas host around 30% of the world's conventional oil reserves, so clearly form excellent reservoirs. However, there are many potential leakage points, into fluvial channels, across the delta and through distributaries, which may act as high perm streaks, and also into offshore canyons. The wide range of depositional settings can lead to compartmentalization, as seen in the Snohvit Field in Norway. More success was seen in the Northern Lights Project, in the Norwegian North Sea, although the initial choice of the Dunlin Fm. was changed to the Johansen Fm in 2016. The main injection target in this formation will be high porosity spit deposits located downstream of an ancient delta, with some concern over calcite cements and mud drapes.

OFFSHORE SETTINGS

Turbidites and lowstand fans have proved to be spectacularly successful reservoirs. They are also considered to be potential CCS targets although there is a propensity for mudstone baffles and barriers due to background deposition between events. Few projects have been undertaken in these settings. The Sleipner Field in Norway utilized lowstand fans of the Utsira Fm. for CCS but this proved very unsuccessful, primarily due to the very low relief reservoir and horizontal permeability barriers. As a result, the reservoir held only 0.1% of the predicted volumes. There were also vertical leaks through gas chimneys, and a 5 m thick shale barrier was breached after three years.

SUMMARY

The Institute for Energy Economics and Financial Analysis (IEEFA) reviewed the performance of 13 major CCS projects and found that 10 failed or underperformed. We have seen that the most common problem experienced in such projects is when pore throats are unexpectedly choked by cementation. Once an exploratory well has encountered high quality reservoir rocks, it appears that assumptions are made that these will continue laterally. Any geologist or geophysicist worth their salt would immediately point out that sedimentary heterogeneity is the norm; after all, it is what keeps us in a job! Other issues include overly optimistic views of reservoir properties and performance.

It is therefore recommended that additional wells are drilled early in the project life in an effort to gain a clearer understanding of the depositional settings in which the CCS target reservoirs were deposited; their 3-D architecture; and their diagenetic history. A sedimentologist and a structural geologist should be core members of the evaluation team. The former can identify possible baffles and high perm streaks, both of which have the potential to disrupt injectivity to the extent that projects may have to be shelved, or at the very least a secondary reservoir identified as a target, often with poorer properties. The structural expert can evaluate the likelihood of sealing versus open faults and fractures.

The next stage of this work is to crunch the excellent IEA (International Energy Agency) 2023 CCUS Projects Database, Paris: http://www.iea.org/data-and-statistics/data-product/ccus-projects-database

The database lists hundreds of worldwide CCS projects, and provides a starting point to explore a wide variety of projects.

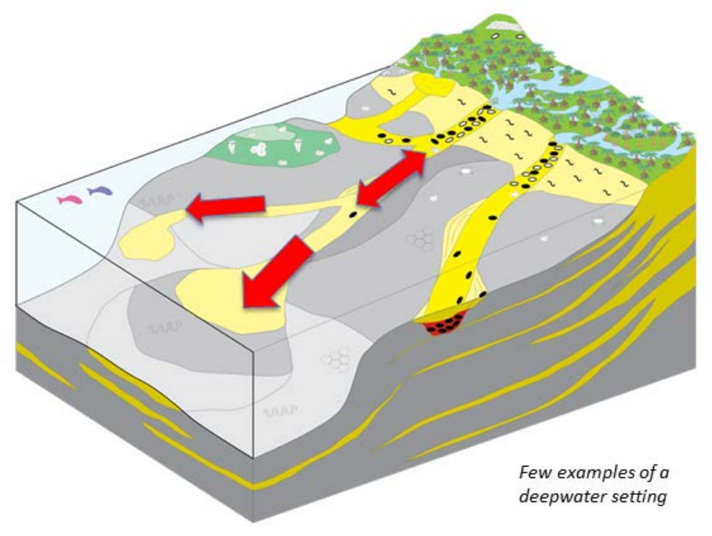


FIG 5 OFFSHORE RESERVOIRS

Small submarine canyon, Miocene Tanjong Formation, eastern Sabah, Malaysia

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