# Low carbon oil production: Enhanced Oil Recovery with $CO_2$ from North Sea Residual Oil Zones

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## Abstract

Residual Oil Zones (ROZ) form when oil has leaked or migrated from a reservoir trap through geological time, leaving a zone of immobile oil. Here we assess the feasibility of ROZ production with $CO_2$ flooding, in a North Sea oil field for the first time. We identify a hydrodynamically produced ROZ, with an oil saturation of 26%, in the Pierce Oil Field of the Central North Sea and adapt established recovery factors for Carbon Dioxide Enhanced Oil Recovery ($CO_2$ EOR) from onshore fields, to estimate oil resource and $CO_2$ storage potential. Our mid case results show that $CO_2$ utilisation increases commercial reserves by 5-20% while storing 15Mt $CO_2$. Based on our calculations $CO_2$ EOR can produce low carbon intensity crude oil from a mature basin and could store more $CO_2$ than is released from the production, transport, refining and final combustion of oil.

## Introduction

Since the discovery of oil by Edwin Drake in 1859[1] the conventional oil industry has developed great expertise in locating positions in the subsurface, into which oil has accumulated by buoyancy, after migration away from its source rock. Within an oilfield, the vertically layered fluid transition is seldom a simple Oil Water Contact (OWC), but is gradational vertically downwards from a zone of mobile oil, the main pay zone (MPZ), into water containing pores. This is defined as a transition zone, the thickness of which depends on capillary forces, below which is the free water level (FWL) (Figure 1A).

What has not been fully understood in the North Sea and most other oil basins globally, is that Residual Oil Zones (ROZ) exist where a number of natural geological conditions have caused the remobilisation of oil out of a reservoir. This natural remobilisation causes the OWC to rise within the oil reservoir leaving behind residually trapped oil (Figure 1B). Although the remaining oil saturation may be similar to an oil field that has undergone primary production and water-flooding, the formation of a ROZ results from natural processes, not from engineered oil production. ROZ oil has not been commercially declared as a reserve, because it historically has not considered recoverable. With many large oil fields in established basins reaching near depletion, and a move to reduce the $CO_2$

emissions of producing oil, the oil reserves and $CO_2$ storage potential in ROZ is of economic and strategic interest.

The concept of these zones holding recoverable reserves has to date only been applied to the United States with work primarily being focussed on the Permian Basin[2], with no previous studies on North Sea oil fields. The origins and resource potential of ROZ below oil fields in North America has been discussed in detail by Koperna et al. (2006)[3], Advanced Resources[4] and Melzer et al. (2006).[5] Melzer et al. (2006)[5] identified three main processes in which oil columns can be naturally drained causing the creation of ROZ: the onset of hydrodynamic flow; breached and reformed reservoir seals; regional or local basin tilt. Here, we investigate how hydrodynamic flow (discussed below) in the Central Graben of the North Sea basin, may lead to the creation of ROZ that can be developed with $CO_2$ injection for enhanced oil recovery ($CO_2$ EOR).

By reviewing literature and well logs, the Pierce Oil Field was identified to have a ROZ. By further analysing well logs and building a 3D geological model of the Pierce Oil Field, we show for the first time that ROZ do occur in North Sea oil fields, and have potential to increase recoverable reserves by up to 20%. With evidence from North America, we propose that ROZ oil can be produced by injection of $CO_2$ as a solvent. Further injection of $CO_2$ into the oil field can more than offset the additional carbon created by producing oil from the ROZ.

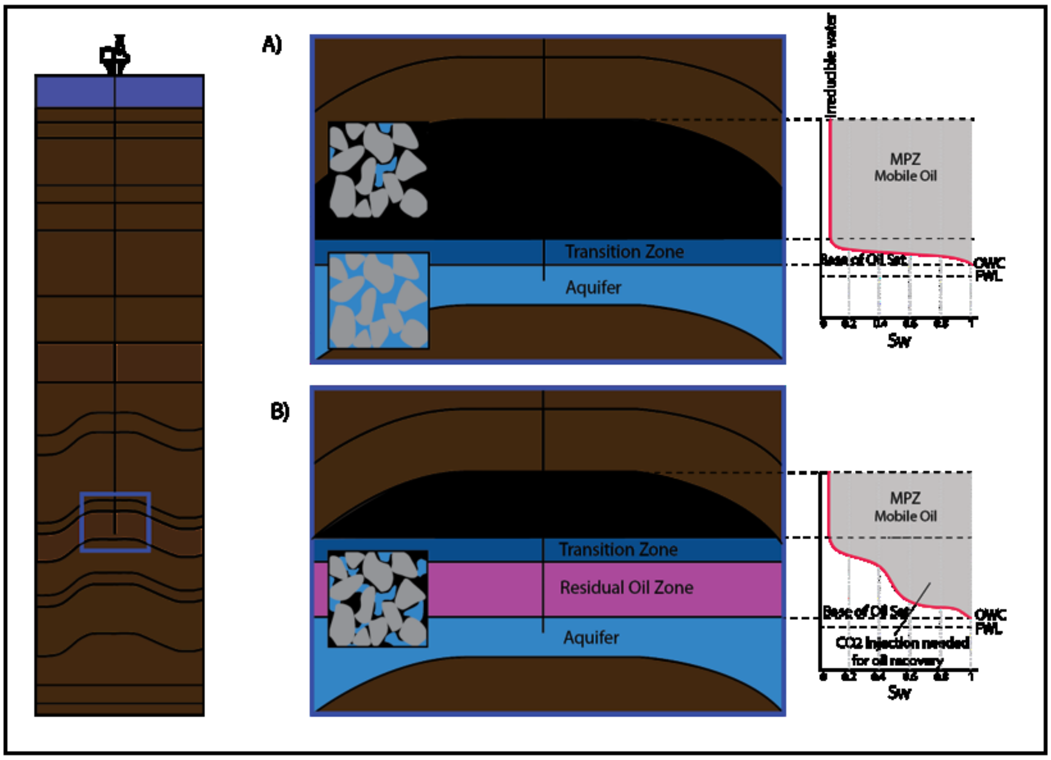


Figure 1 – A) Schematic representation (left) of a generalised oil field with (centre) an oil column and transition zone below. Inset graphs (right) show that oil saturation (1-Sw) varies from ~90% (10% irreducible water saturation) above the OWC to 0% at the bottom of the transition zone (100% free water level- FWL). B) Schematic representation of oilfield with ROZ, where the oil column has previously been thicker. Oil has been removed by natural geological process, such as hydrodynamic tilting, and has left a ROZ. Although ROZ will produce only water when developed under primary or secondary production, they produce oil when $CO_2$ is injected.

## Carbon Dioxide Enhanced Oil Recovery and Residual Oil Zones in North America

In North America, $CO_2$ EOR is an established technology used to produce incremental oil from oil fields that have been depleted or water flooded. The injection of pure $CO_2$ reduces oil viscosity (increasing oil mobility) and increases reservoir pressure and oil volume[7–10] causing residually trapped oil to move towards production wells. Developed commercially in the 1970s, $CO_2$ EOR is currently utilised in over 130 oil fields in United States[11] where it is primarily deployed in oil fields that have been depleted through engineered production.

In the Permian basin of Texas, 8 fields are currently using $CO_2$ EOR to produce oil from the ROZ, with over 6500 barrels of oil being produced per day[12,13]. The fields that are currently producing from the ROZ use $CO_2$ injection to produce from both the ROZ and the MPZ above. However $CO_2$ EOR from the ROZ are not only targeted at zones which have depleted MPZs, as one of the 6 currently planned $CO_2$ EOR ROZ developments are targeting a ‘greenfield ROZ’ where no depleted field exists above the ROZ[12]. These ‘greenfield’ zones, the formation and history of which is explained in detail in Trentham et al. (2012)[12], are thought to have been formed when a combination of water charge and tectonic uplift, which causes elevated piezometric pressure[6], has caused large regional formations, such as the San Andreas Formation, to be 'naturally water-flooded'. This water charge is believed to have swept the oil in paleo-traps, leaving regional scale zones of residual oil behind[12].

Although only a small number of fields are currently producing from the ROZ, the resource potential for the US is estimated to be large. As summarised by Godec et al. (2013)[13] work by ARI and Melzer Consulting has identified up to 42 billion barrels of oil in place below existing fields in the Permian, Big Horn and Williston basins[4,14,15]. Further work by Melzer Consulting has highlighted that up to 100 billion barrels of oil in place may exist in 'greenfield' ROZ fairways in the Permian basin alone [12]. Initial reservoir modelling work estimates that 13 billion barrels of oil is economically recoverable from ROZ below established oil fields in the Permian basin and 20 billion barrels may be economically recoverable from 'greenfield' ROZ in the Permian basin with $CO_2$ injection. Kuuskraa et al. (2013)[16] estimate that the $CO_2$ demand from developing ROZ below US oil fields and 'greenfield' ROZ may be up to 13 billion metric tonnes over the life of the projects. Considering the US has annual $CO_2$ emissions of over 5 billion Mt the potential $CO_2$ demand from $CO_2$ EOR is not insignificant.

**Characterising Residual Oil Zone potential at a field scale**

Once a target ROZ has been identified a number of studies have proposed different methods to determine both the existence and potential recoverability of oil from the ROZ. Honarpour et al. (2010)[17] completed a rock-fluid characterisation for miscible $CO_2$ injection in the ROZ at the Seminole field in the Permian basin. They present a method for firstly estimating the remaining oil saturation through a range of core and core scale water-flood tests before also characterising formation anisotropy and scale dependent permeability. Then residual oil saturation after miscible $CO_2$ flooding is predicted from core scale $CO_2$ flood tests at reservoir pressures and temperatures. The rock and fluid properties, when integrated into a geocellular model, can then be used to run a compositional $CO_2$ flood to assess field scale recoverability from the ROZ.

Pathak et al. (2012)[18] also present a method for evaluating the ROZ potential at the Means field in the Permian basin. Focussing on reservoir uncertainty and methods to predict the remaining oil saturation in a field, Pathak et al. (2012)[18] note that the major reservoir uncertainties derive from defining the remaining oil saturation, the recovery efficiency and timing of oil recovery of $CO_2$ EOR in the ROZ and the presence of leach zones or thief intervals. They also note that other reservoir uncertainties such as facies distribution, the presence of vertical flow barriers and baffles and well injectivity limitations, although relevant, are less significant uncertainties. Here a similar method to that described in Honarpour et al. (2010)[17] is applied to the Pierce Oil Field to estimate the oil resource potential and $CO_2$ storage resource in the ROZ. To date, this resource estimation has not been completed on a North Sea oil field.

## Hydrodynamic principles

Hydrodynamic flow of ‘active’ aquifer water upwards and outwards from deep basin geopressured zones in the Central Graben of the North Sea causes OWCs to tilt, leaving zones of residual oil. In North America, ROZ created through hydrodynamic processes typically contain 10-40% immobile oil in the pore space.[17,19] This is a similar oil saturation to many of the fields in the North Sea basin which have undergone primary and secondary production (water-flooding). If similar oil saturations are found in North Sea ROZ, then these are targets for $CO_2$ EOR.

Under static aquifer conditions the hydrocarbons within an oil accumulation have a flat contact with the saline aquifer brine below. If the structure has been filled to spill, the structural spill point will control how much hydrocarbons the trap can hold. If the structure continues to be charged with migrating oil, then hydrocarbons will leak from the structural spill point. However in oil fields with an underlying active aquifer, hydrodynamic flow and the resultant tilting of the OWC may cause the spill point to move to one that is hydrodynamically controlled.[20–24] When this occurs creating an asymmetric hydrocarbon trap, the new spill point may be deeper than the structural spill point in the direction of pressure decrease, trapping additional hydrocarbons beyond the known trap. Towards the direction of aquifer inflow, the OWC will move above the structural spill point. Where this OWC has retreated from the structural spill point to the new hydrodynamically controlled OWC, a zone of residual oil is left (Figure 2).

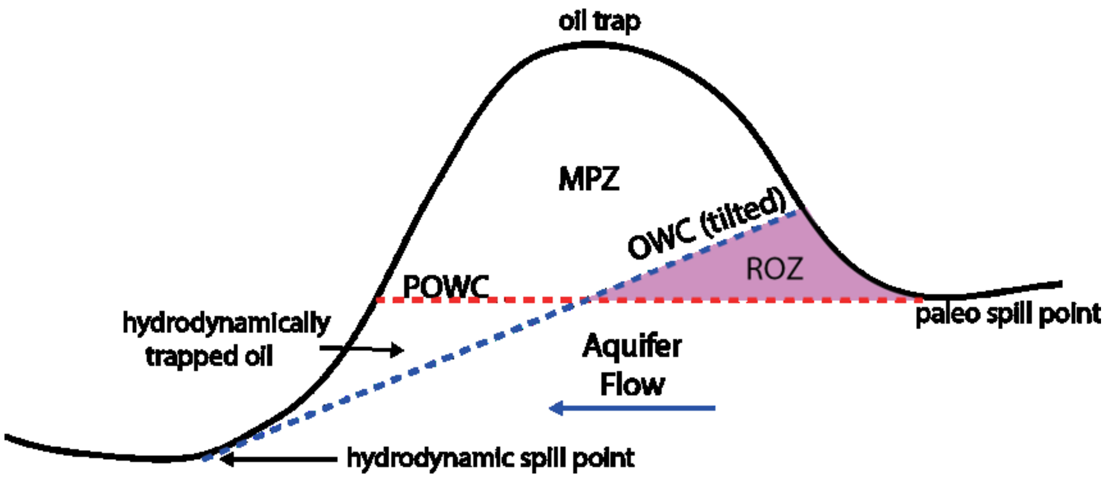


Figure 2- Schematic representation of hydrodynamic flow and the creation of ROZ. The paleo oil water contact (POWC), before the onset of hydrodynamics, is highlighted in red. The pressure gradient across an oil field causes the FWL (free water level, here noted as oil water contact) to tilt in the direction of lowest pressure, leaving a wedge of residual oil (pink), with a new hydrodynamic spill point being created.

## Residual Oil Zone potential at the Pierce Oil Field- a case study

The Pierce Oil Field is located in Blocks 23/22a and 23/27 of the UK Central North Sea, adjacent to the UK/Norway median line in 85m of water. The field is characterised by the accumulation of oil and free-gas caps within the Palaeocene Forties Sandstone Member, on the flanks of two Permian Zechstein salt diapirs that are separated by a 1.5km wide structural saddle.[25–27] The field is characterised by large variations in the measured OWCs which were identified by both well log and pressure data in the appraisal wells that were drilled in the 1970s. Across the field a general deepening trend in the OWC towards the west is observed with over 300m of vertical relief between the shallowest and deepest OWCs observed in the field (Figure 3). This equates to a dip of 90m/km.[20] Although different theories exist to explain the variation in OWCs at the Pierce Field,[26,28] a number of studies have proposed that it is hydrodynamically controlled.[20,21,29] We propose that hydrodynamic tilting of the OWC has aided in the creation of a ROZ, in the definition of Melzer et al. (2006).[5]

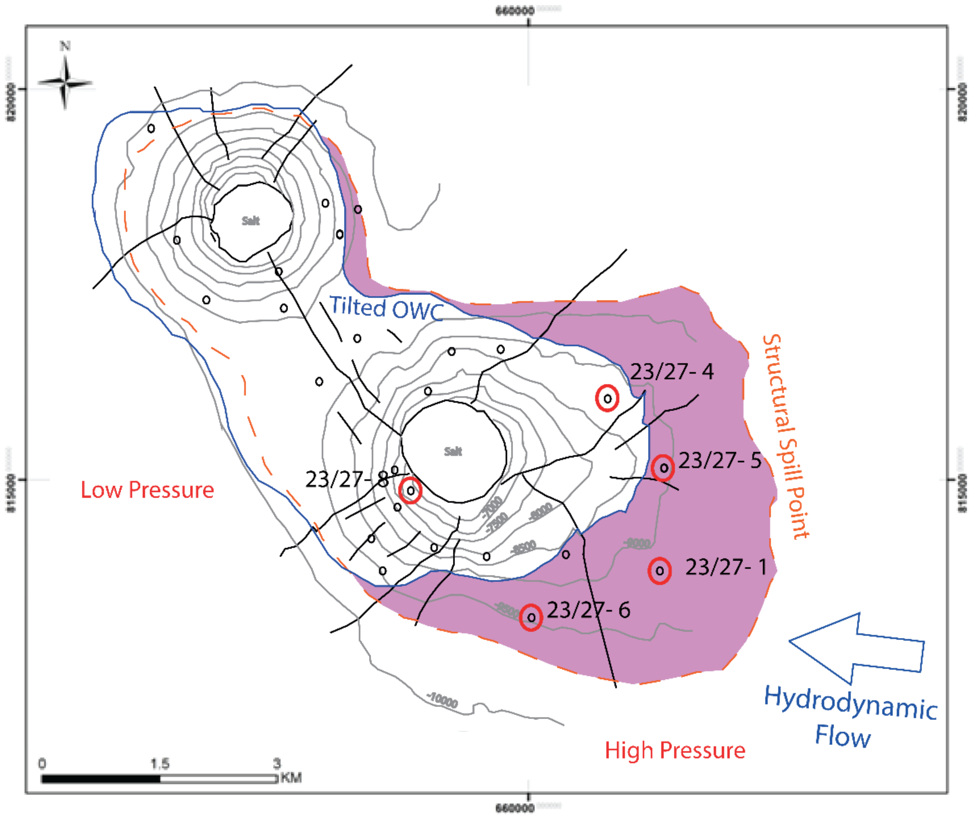


Figure 3- Top reservoir structure map of the twin salt diapir Palaeocene Pierce Field, adapted from Porter (2011).[27] The present day oil water contact (blue) has a vertical relief of 300m and is below the structural spill point in the NW sector of the field but sits above the structural spill point in the SE sector of the field. The ROZ (pink) lies between the structural spill point and the current OWC in the SE sector of the field. Before the location of the OWC was known and the hydrodynamic theory proposed, 4 wells (23/27- 1,4,5,6) were drilled in the SE sector above the structural spill point. N.b well 23/27-4 has been interpreted by some to lie down dip of the OWC and so has been included in this study.[27]

The identification of a producible ROZ at South Pierce has not been made previously, although a number of studies have highlighted that wells that were drilled in the SE sector of Pierce within the structural closure were 'dry holes' i.e. did not flow oil during drill stem tests.[20,21,29] These studies infer that wells in the SE sector of the South Pierce Field contain residual oil due to a retreating hydrodynamically controlled OWC but do not identify it as a producible zone.

## Methods

### Constructing a static geological reservoir model of the ROZ at the South Pierce Field

To estimate the volume of oil in place and potential $CO_2$ storage volume of the ROZ at the Pierce Field a basic 3D geological model was constructed using MOVE™. A summary of the model building method can be seen in Figure 4. The top Forties Horizon was constructed using a structural contour map derived from 3D seismic.[27] Well deviation data and composite logs were taken from the UK Oil and Gas Data- Common Data Access Database (CDA) for 14 appraisal wells drilled throught the North and South Pierce Field. Top Forties Member sandstone well tops were taken from composite well logs and used to tie surfaces to the correct depth (TVDSS). It is thought that the depth uncertainty in the seismic derived surfaces is around 30-60m, due to the difficult seismic imaging at the salt- reservoir boundary. Due to the lack of publicly available seismic data, or structural contour maps for the Bottom Forties Member, the bottom Forties Member surface was projected from the top reservoir surface using an orthogonal constant bed thickness of 122m. Although this thickness was estimated from well data and from thickness data within Birch & Haynes (2003)[25] it only represents an average for the formation. Well tops derived from composite well logs were also used to tie the bottom surface to the correct true vertical depth (TVDSS). A surface depicting the pre-production tilted OWC was constructed from contour data presented in Porter (2011).[27]

As the ROZ is depicted by the zone between a paleo oil water contact (POWC) and a pre production OWC, the POWC also had to be defined for Pierce. Although there is debate within the literature, it was assumed for this study that the POWC lies at the depth of the structural spill point for the trap at -3008m TVDss.[25] To create a bottom surface for the deepest extent of a ROZ, the horizontal surface representing the structural spill point was merged with the bottom Forties surface, for when the bottom Forties is above -3008m (above the structural spill point). The top surface for the ROZ was created by merging the present day pre-production OWC (where it is split by the top and bottom forties surface) with the Top Forties surface. Creating these two surfaces that represent the top and bottom extents of the residual zone allowed a geocellular volume to be created that could be populated with core and well log data to estimate the oil in place and $CO_2$ storage capacity of the ROZ (Figure 4). As can be seen in Figure 5, in wells 23-27-1 and 23-27-5 the ROZ extends from the top Forties Sandstone Member to bottom Forties Sandstone Member. In well 23-27-4 only around 12m of ROZ is penetrated. The ROZ at South Pierce was found to have a bulk rock volume of 982 ± 184×$10^6$ $m^3$. The uncertianity in the estimate is dervied predominantly from the seismic depth uncertaintity of 30-60m in the 122m thick

Forties Sandstone Member which equates to an error of 38% (45m error in 122m thickness). However because surfaces are tied to well data this seismic error is not present throughout the surface. By combining the well error, taken as 0%, and the seismic error of 38% an error of 19% is used for the total volume.

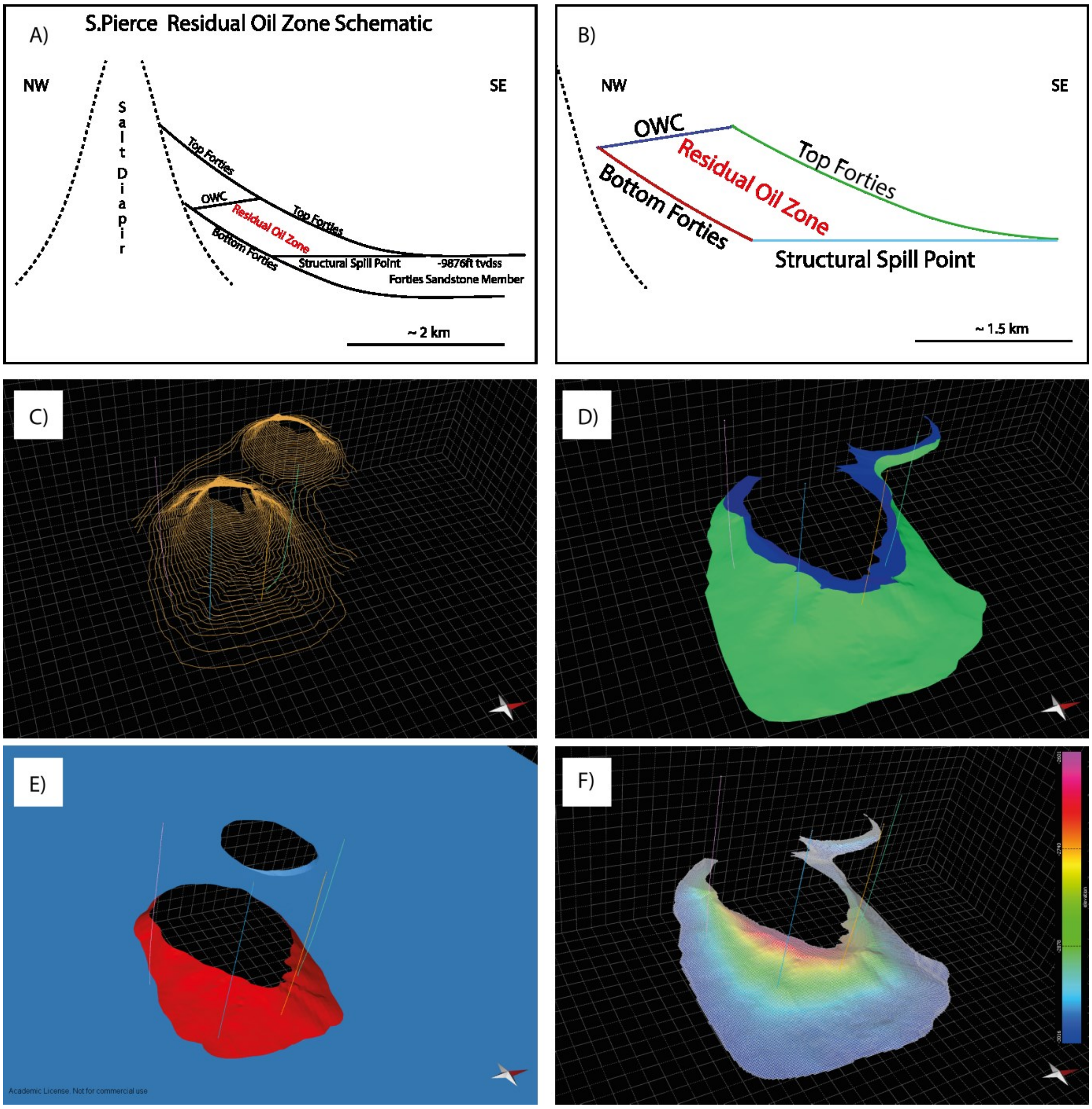


Figure 4 – A) South Pierce schematic summary B) 4 surfaces selected to build residual oil zone volume C) Top reservoir surface contours. Top surface was constructed from published top reservoir structure maps and corrected using well data D) Top Forties surface (green) was cut and merged with the current oil water contact surface (dark blue) E) The bottom Forties surface (red) was constructed by projecting the top reservoir surface with a constant bed thickness of 122m. Well data was also used to correct the surface depths. F) Geocellular model representing the bulk rock volume of the ROZ at South Pierce- colours represent depth with red shallow and blue deep.

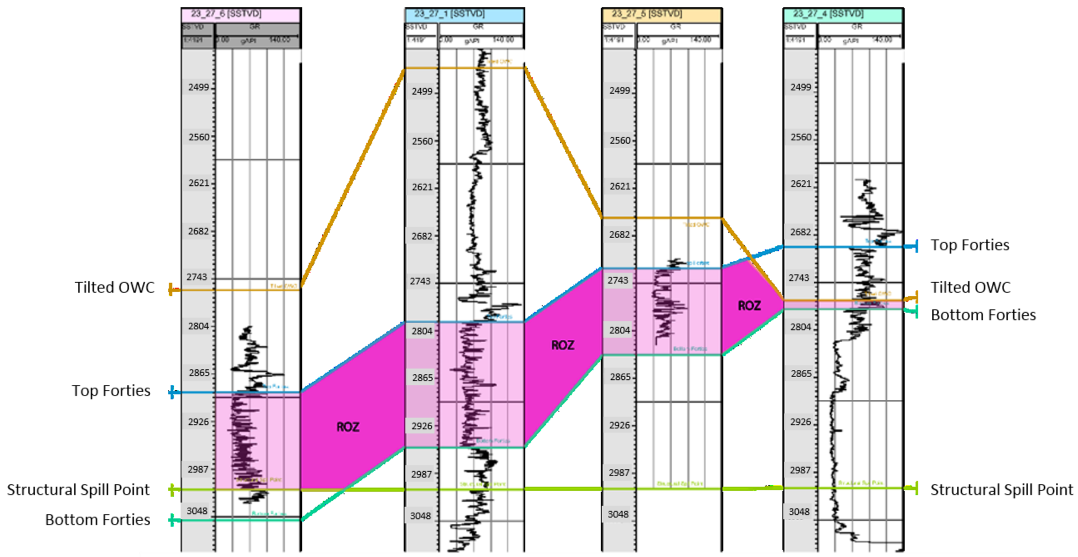


Figure 5 - Well log summary with gamma ray of the four wells thought to penetrate the ROZ at the South Pierce Field.

Log and core data from four wells (23/27- 1,4,5 & 6) (See Figure. 3 for location), which penetrate the ROZ at South Pierce were used to populate the bulk rock ROZ volume with porosities and NTG. Residual oil saturation values were available from core analysis. However it is thought that due to post core extraction leakage that these values would under estimate the in-situ remaining oil saturation.[17,30] Techniques such as sponge coring, where the expelled oil is captured after core cutting, are not thought to have been carried out in the core analysis of the wells at South Pierce. As highlighted by Honarpour et al. (2010)[17] pressure retained coring is the preferred technique for determining remaining oil saturations, but is not currently practised due to the costs and risks involved.

In situ oil saturation was therefore estimated using Archie's water saturation (Sw) equation[31] (See Supplementary Information for more details). This well log method, alongside core analysis, log inject log (LIL) and chemical tracer tests, was also used by Pathak et al. (2012)[18] to determine oil saturation for EOR projects. Chang et al. (1988)[30] who evaluated and compared different methods to determine residual oil saturation estimated that oil saturation predictions using resistivity logs may be slightly higher than in other methods. It also must be noted that the oil saturations in a ROZ will be locally variable and the estimation of oil saturation will never be without uncertainty.

**Monte Carlo simulation of data at South Pierce**

To estimate the total oil in place for the ROZ at South Pierce a Monte Carlo approach was used using R-Studio™. For bulk rock volume, NTG and porosity random sampling between the minimum and maximum range of values was used for the 20,000 iterations run. For porosities a random value was sampled between the range of mean porosity from each well. This was completed using a 'runif' statement to randomly sample a value between the input ranges. Water saturation values were sampled from a merged dataset of all minimum, mid and maximum $S_w$ from all four wells, which equated to 2244 $S_w$ values. No well was given any sampling preference over another. Recovery factors were also estimated to calculate the recoverable reserves from the ROZ at South Pierce. Given the lack of experience of $CO_2$ injection into ROZ in the North Sea, analogue recovery factor values of 5-25% of oil in place, were taken from the literature (see Discussion for more details).[12,16,32] Random sampling between these minimum and maximum recovery factors was also incorporated into the Monte Carlo simulation. A summary of the ranges used are displayed in Table 1 below. This led to a final equation in R-Studio being run with 20,000 iterations:

$$Recoverable\ reserves = sampled\ bulk\ rock\ volume \times sampled\ porosity \times sampled\ oil\ saturation \times sampled\ NTG \times sampled\ recovery\ factor \times formation\ volume\ factor$$

Table 1 – Summary table of ranges used within Monte Carlo Analysis

| ROZ Parameter | Ranges used in Monte Carlo |
|---|---|
| Bulk Reservoir Volume $m^3$ (geo-cellular volume) | 797,510,075 – 1,165,591,647 |
| Water Saturation (well logs) | 0.58 - 0.94 |
| Porosity (core tests) | 0.17 - 0.21 |
| NTG (well logs) | 0.44 - 0.74 |
| Recovery factor | 0.05 - 0.25 |

**Results and Discussion**

As can be seen in Figure 6, oil was present at low saturations at wells that are interpreted to penetrate the ROZ. Mean oil saturation across the 4 wells is 14% (stdev 9.8%), when calculated using core analysis data. Using well log resistivity data to estimate oil saturation leads to a higher mean oil saturation. The mid value water saturations for the sand intervals within the Forties Sandstone Member, based on the Archie water saturation method, were calculated to lie between 71% and 85%, with minimum values lying between 58% and 72% and maximum values lying between 80% and 94% (Table 2 in Supplementary Information). Using the same Archie water saturation method for all $S_w$ data points in the four wells, a mean value of 74% - 26% oil saturation- (st dev 16%) was found. These higher and likely more representative oil saturations calculated using Archies water saturation method were used to calculate the oil in place for the South Pierce ROZ.

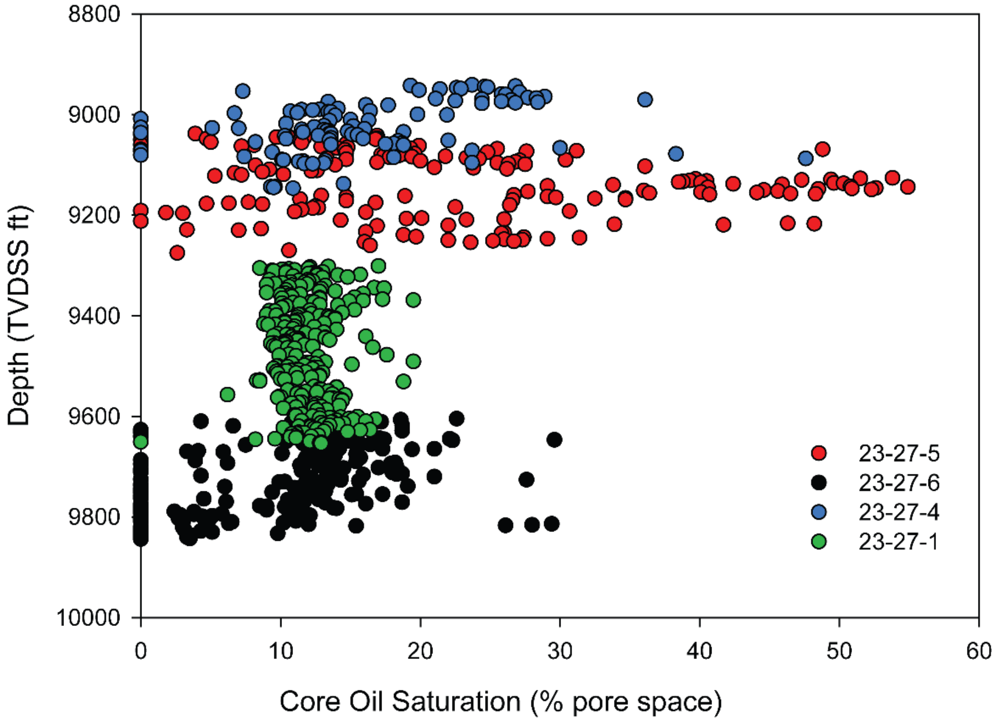


Figure 6- Compilation of core residual oil saturations from laboratory core tests at the four wells thought to cut through the ROZ at the South Pierce Field. The saturations given represent % pore space. Across the 4 wells the average core oil saturation is 15% but reaches values of up to 55%. Saturations calculated by well log analysis are higher at 26% average. Reservoir modelling and real field developments show that 5-25% of this oil can be recovered and can add additional commercial reserves not previosuly included in a fields reserves estimates (see Discussion for more details).

Using a Monte Carlo approach for the ROZ at South Pierce, oil in place values of 106, 179 and 291 MMbbl for P90, P50 and P10 respectively were estimated for the ROZ. Recoverable oil reserves for the South Pierce ROZ are estimated at 7, 17 and 34 MMbbl for P90, P50 and P10 respectively (Table 2). Given the main oil column in the Pierce Field had initial recoverable reserve values calculated of 42, 84 and 120 MMbbl for P90, P50 and P10 respectively,[28] it can be estimated that the $CO_2$ EOR potential of the ROZ at the South Pierce Field adds around 20% to the recoverable reserves at the Pierce Field.

Table 2 – Summary of Monte Carlo results for $CO_2$ EOR from the ROZ at South Pierce. Recoverable reserves estimated using a range of recovery factors of 5-25% and a formation volume factor of 1.5. $CO_2$ demand is a minimum commercial requirement, calculated using storage factor of 0.33 $tCO_2$/bbl of oil produced. $CO_2$ storage is a maximum potential calculated using a storage factor of 0.9 $tCO_2$/bbl of oil produced.

| | Min | Mid | Max |
|---|---|---|---|
| **Forecast** | P90 | P50 | P10 |
| **Oil in Place m3** | 16,822,843 | 28,473,651 | 46,259,511 |
| **Oil in Place (MMbbl)** | 106 | 179 | 291 |
| **Recoverable Reserves (MMbbl)** | 7 | 17 | 34 |
| **$CO_2$ Demand (Mt)** | 2 | 6 | 11 |
| **$CO_2$ Storage Potential (Mt)** | 6 | 15 | 31 |

## $CO_2$ storage at Residual Oil Zones

It is thought that $CO_2$ EOR from ROZ will have similar operating parameters to $CO_2$ EOR operations that produce from conventional oil fields.[12] During the $CO_2$ EOR process residual trapping of $CO_2$, $CO_2$ dissolution and inefficient $CO_2$ sweep results in large fractions of injected $CO_2$ being stored permanently in the reservoir porspace and fluids.[33,34] However a proportion of the $CO_2$ that is injected will return to the surface and be recycled. If recycled $CO_2$ is not diverted for injection in a different field it can be assumed that all $CO_2$ injected to increase recovery at a field will be stored at the end of the project (minus any $CO_2$ lost as fugitive emissions).[35]

Based on $CO_2$ storage factors presented by Ferguson et al., Godec et al. and SCCS,[36–38] a figure of 0.33 t/bbl was chosen to estimate the $CO_2$ demand at the ROZ at South Pierce. When applied to the value of recoverable reserves detailed in Table 2, the $CO_2$ demand at South Pierce ROZ is 2, 6 and 11 Mt of $CO_2$ for P90, P50 and P10 respectively. These estimates do not represent a maximum capacity for the zone, but only estimate the mass of $CO_2$ that is required to recover oil from the ROZ. If the storage factor of 0.9t $CO_2$/bbl, which represents $CO_2$ storage optimised $CO_2$ EOR where additional $CO_2$ is injected into the aquifer below[35,39] is used, higher $CO_2$ storage estimates of 6, 15 and 31 Mt for P90, P50 and P10 respectively are found (Table 2). There are then a range of possibilities to store increasing ammounts of $CO_2$ by utilising the active aquifer in addition to the reservoir. As first defined by the International Energy Agency,[39] storage of $CO_2$ in excess of the minimum, we title $CO_2$ EOR+ will require either a political and regulatory mandate, or a financial payment/fine avoidance to reward $CO_2$ stored.

**North Sea Residual Oil Zone potential**

We show in this study that the South Pierce Field holds potential for $CO_2$ EOR development in the ROZ. Most geological plays for conventional hydrocarbon exploration are specified around a combination of age of geological strata with structure or stratigraphic layering to physically trap buoyant migration within a basin. By contrast, identification of ROZ plays requires a different approach. Based on work by Dennis et al.,[20,21] we have identified multiple hydrodynamic ROZ targets, with tilted OWC in the Central Graben. These are geographically grouped in the region affected by deep aquifer outflows draining the high geopressure parts of the deep North Sea. In contrast to conventional hydrocarbons, this play is controlled by brine flow in the deep subsurface, and so spans between a range of reservoir ages and structure types. Hydrodynamically controlled tilted OWCs have been proposed in fields ranging in age from Jurassic[40,41] to Cretaceous[20,40,42–44] and Palaeocene[20,45] in age. It is therefore likely that hydrodynamic ROZ potential exists in a number of other North Sea Fields.

**$CO_2$EOR recovery factors at Residual Oil Zones**

This study highlighted the existence of hydrodynamically controlled ROZ in the North Sea by interpreting well data[46], however the recoverability of oil from these zones is one of the key areas of uncertainty. In this work, it was unfeasible to conduct core flood tests on core from the South Pierce Oil Field to estimate irreducible oil saturation. Therefore we propose that using analogue field wide recovery factors is sufficient to estimate the range of recovery rates that occur when $CO_2$ flooding ROZ. While the 8 fields currently running $CO_2$ EOR from the ROZ in the US are successful[32], the duration of these projects is not long enough to have confidently established a benchmark recovery factor. Hill et al. (2013)[32] suggest a conservative recovery factor of 20% of oil in pace but state that recovery factors could reach 30%, with a maximum achievable recovery factor based on $CO_2$ EOR recovery rates on the main pay zone of 42%[32]. Trentham et al. (2012)[12] suggest that recovery rates of 10-20% can be achieved from the ROZ. This is supported by the white paper by Kuuskraa (2010), who suggests recovery rates of 17-18% of oil in place at the start of $CO_2$ injection.

For estimating recovery factors from North Sea ROZ, where development and well drilling would take place offshore, with greater costs, it is likely that lower recovery factors will be achieved. Although well spacing is expected to be higher in the North Sea a number of studies have suggested that reservoir conditions will lead to similar surface volumes of $CO_2$ being needed for successful EOR operations. Goodyear et al. (2003)[47] state that although the majority of UKCS fields lie at a greater depth than US fields, $CO_2$ densities (500-1000 $kg/m^3$) would be similar due to the counteracting effect of higher temperatures. It is also proposed that higher permeabilites and porosities in many UKCS oil fields will counteract the well spacing issues. However Goodyear et al. (2011)[48] and Tzimas et al. (2005)[49] highlight the effect that these high permeablilities have on gravity segregation which will also be amplified by large well spacing. They do however state that this detrimental effect may be combatted by drilling horizontal wells, but that attention should be paid to the inter-well pressure decrease that may drop reservoir pressure below the minimum miscibility pressure when horizontal wells are utilised.

Given these uncertainties, the broad range of recovery factors used within this study (5-25%) were chosen to represent the uncertainty in developing ROZ in an offshore setting in a basin that has seen no $CO_2$ EOR development. It is recommended that a more detailed reservoir model and reservoir simulation would be needed to increase the confidence of the reserves potential.

It must also be noted that while this study focusses solely on the ROZ at the Pierce field and does not asses the $CO_2$ EOR potential from the main oil column, in many cases it may be best economically to develop ROZ alongside a broader $CO_2$ EOR development. As referenced in the introduction of this paper, this is the most common practice in $CO_2$ EOR projects that are producing from the ROZ in North America[12]. There, wells have been extened to penetrate through the main oil column and into the ROZ and produce oil from both zones. In the North Sea this would also likely be a first step for a $CO_2$ EOR ROZ development, where $CO_2$ can be used to increase recovery rates from a well characterised main oil column, with ROZ adding to recoverable reserves and $CO_2$ storage resource as an additional target.

**A low carbon oil production solution**

Although the reserves potential and $CO_2$ storage potential highlighted in this study are significant, the development of ROZ with $CO_2$ EOR faces a number of non-scientific challenges.[48] These include: profitability in a oil price lower than $60/bbl, or field decomissioning rather than engineering a change of use and extension of life.

The guaranteed availability of $CO_2$ is persistent paradox, given the IPCC's (2014)[50] strong recommendations on Carbon Capture and Storage (CCS), and lack of any large scale projects in Europe.[51] During the formulation of a whole-system energy and climate policy, it is important to recall that other EOR options, unlike $CO_2$ EOR, do not allow for a transition towards $CO_2$ storage. Stewart and Haszeldine (2015),[35] showed that $CO_2$ EOR could produce oil with a carbon intensity of 0.135 $tCO_2$/bbl of oil produced and as low as 0.06 $tCO_2$/bbl if flaring and venting of produced methane gas was reduced to a minimum of 1%. Although only marginally lower than production from some conventional oil fields (0.08 UK conventional production),[52] this carbon intensity is significanlty lower than other sources such as Nigerian and Venezualan crude (Figure 7).[52] For the South Pierce Field case study this would mean that to produce 17 MMbbl of oil (P50 recoverable reserves), 2.3 Mt of $CO_2$ equivalent would be emitted or 0.88 Mt $CO_2$ equivalent if flaring is reduced to 1%. These emissions are smaller than the 15Mt of $CO_2$ stored (P50) in the $CO_2$ EOR+ process. If emissions from the transport, refining and final combustion of crude oil are also included then an additional 7.9 Mt $CO_2$ equivalent ($CO_2$e) will enter the atmosphere. Therefore, as seen in Figure 7, disregarding any emissions associated with the $CO_2$ before it is transported offshore, this $CO_2$ EOR+ process could store more $CO_2$ than produced, with a net 6.6 Mt of $CO_2$ stored. As seen in Figure 7, other oil production methods noted are net emitters of $CO_2$.

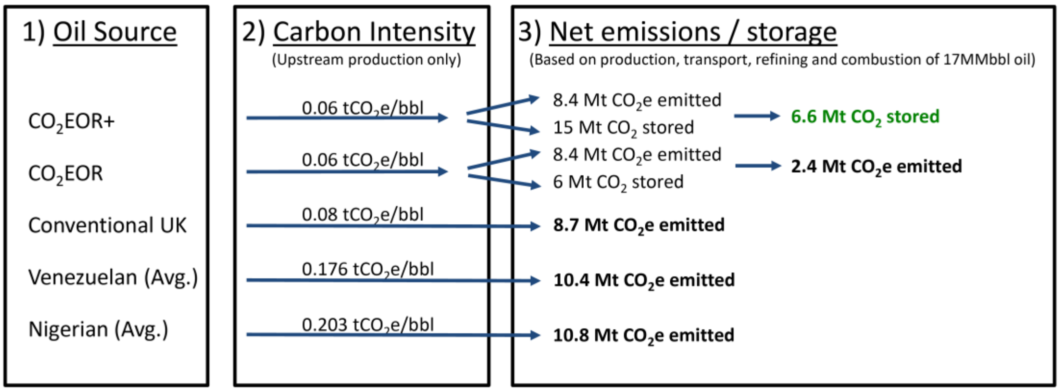


Figure 7 – Carbon intensity and net emissions / $CO_2$ storage from different oil sources. Carbon intensities represent upstream production only and are taken from Stewart and Haszeldine, (2015)[35] ($CO_2$EOR and CO2EOR+) and from Gordon et al. (2015)[52] (conventional UK, Venezuelan crude and Nigerian crude). Carbon intensities for $CO_2$ EOR and $CO_2$ EOR+ do not incorporate $CO_2$ stored. Net emissions / storage values in box 3 are shown in bold. Net emissions in box 3 represent emissions from producing (as in box 2), refining (0.03 t$CO_2$e/bbl), transporting (0.004 t$CO_2$e/bbl) and combusting (0.4 t$CO_2$e/bbl) 17 MMbbl of oil.[35] $CO_2$ EOR+ is the only process that stores more $CO_2$ than is emitted from the production, refining, transport and combustion of oil.

## Conclusions

ROZ are not currently regarded as producible in the North Sea basin, so this oil is not declared as a resource. We identify a commercial opportunity to create new value by efficient use of existing hydrocarbon basins in an environmentally sustainable approach.

$CO_2$ flooding can be both used to maximise production in mature oil fields and store large volumes of $CO_2$. We recognise the first North Sea ROZ, as a potential resource, in the Pierce Oil Field, North Sea, Central Graben. Residual oil saturations at the South Pierce ROZ were on average 26%, of which a significant proportion could be produced by $CO_2$ EOR, and add up to 20% to the initial oil field reserves. While this study attempts to quantify the range of volumes of oil that could be produced and $CO_2$ that could be stored from ROZ, significant further research, such as detailed reservoir simulations, would be needed before any project is undertaken.

We propose that maximum utilisation of $CO_2$ (named $CO_2$ EOR+) will produce low carbon intensity oil and will store more carbon than is released from the production, transport, refining and combustion of the produced crude. With the development of $CO_2$ infrastructure, this practice can be a first step to $CO_2$ storage development in the North Sea basin.

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