Hydro'Carbon' systems and what it can teach us about putting the 'Carbon' back, a CCS systems case study

Dr. James R Johnson

Institute for Energy Technology

Introduction

Exploring for hydrocarbons is an incredibly complex pursuit. This is exemplified by Canadian exploration and exploitation budgets in 2023 – 40.5 billion CAD (StatCan, 2024). However, on another level it is very simple and can be broken down into the four basic play elements that are introduced in any university course that touches on hydrocarbon exploration. They are source, migration, reservoir, and trap/seal (SPE, 2024). There are strong similarities between the key elements of hydrocarbon systems and carbon capture and storage (CCS) systems. While not identical, the learnings from one can be employed to optimize the other. Here we explore how understanding the basics of a hydrocarbon system can help with CCS applied to sedimentary systems with a saline aquifer.

Source

Hydrocarbons are organic material (OM) composed entirely of hydrogen and carbon atoms that have been trapped within rock through sedimentary processes as kerogen, typically shales (i.e. source rocks).

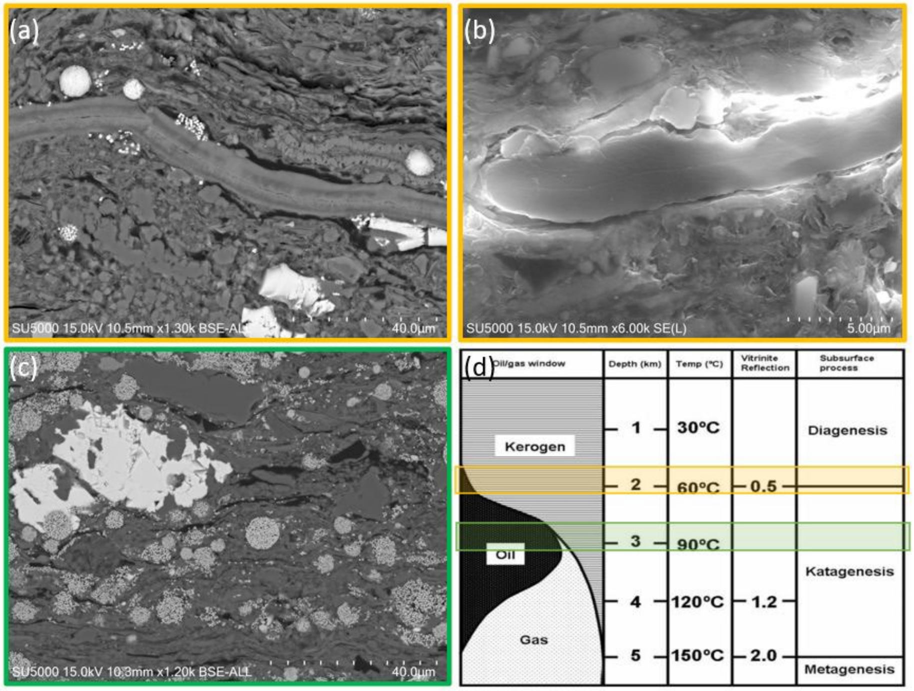


Figure 1 *– (a) SEM image of well 16/8-3 S (Norwegian North Sea) highlighting immature kerogen lenses in black prior to cracking, with (b) a zoomed in image of a single kerogen lens surrounded by quartz and clay minerals. (c) SEM image of another well 15/9-4 (Norwegian North Sea) showing kerogen lenses that have partially cracked represented by black kerogen lenses with a grey ring around the outside edge. (d) Oil and gas window (from Tissot and Welte, 1984) with the oil/gas window that the samples from 16/8-3 S (yellow) and 15/9-4 (green) are currently in.*

To be considered an economic source rock 2 wt.% total organic carbon (TOC) kerogen is an industry and academic standard that has been widely adopted (BGS, 2014). The conversion of the hydrocarbon from a solid (i.e. kerogen) to a fluid/gas occurs when the necessary temperature and pressure thresholds have been attained, and are referred to as the oil/gas window (Tissot and Welte, 1984). The reason for a window rather than a single point is that it is a combination of temperature, pressure, and time that allow for the conversion to take place (Gretener and Curtis, 1982; Johnson et al., 2022b). Figure 1 shows a comparison of SEM images of shale containing kerogen that is immature and that have been partially cracked.

For CCS, the source could be considered analogous to the capturing of CO_2. This is done in a variety of ways. However, they can be broken down into direct air capture and industrial use capture (DNV, 2024). Direct air capture includes biological processes (e.g. macroalgae, microalgae) as well as technological (e.g. Climeworks). Industrial use capture can be further broken down into three categories, they are: post-combustion, pre-combustion, and oxy-fuel combustion (LSE, 2024). Once captured, the CO_2 can be transported to an injection site.

Migration

For hydrocarbon systems, migration describes the movement of fluid/gas from the source rock to a container (i.e. reservoir) with an effective lid (i.e seal/trap). This process is simpler to outline than to understand. It requires expulsion from the low porosity (Φ), low permeability (K) source rock - the dynamics of which are still being debated and researched (e.g. Kobchenko et al., 2014; Johnson et al., 2022c).

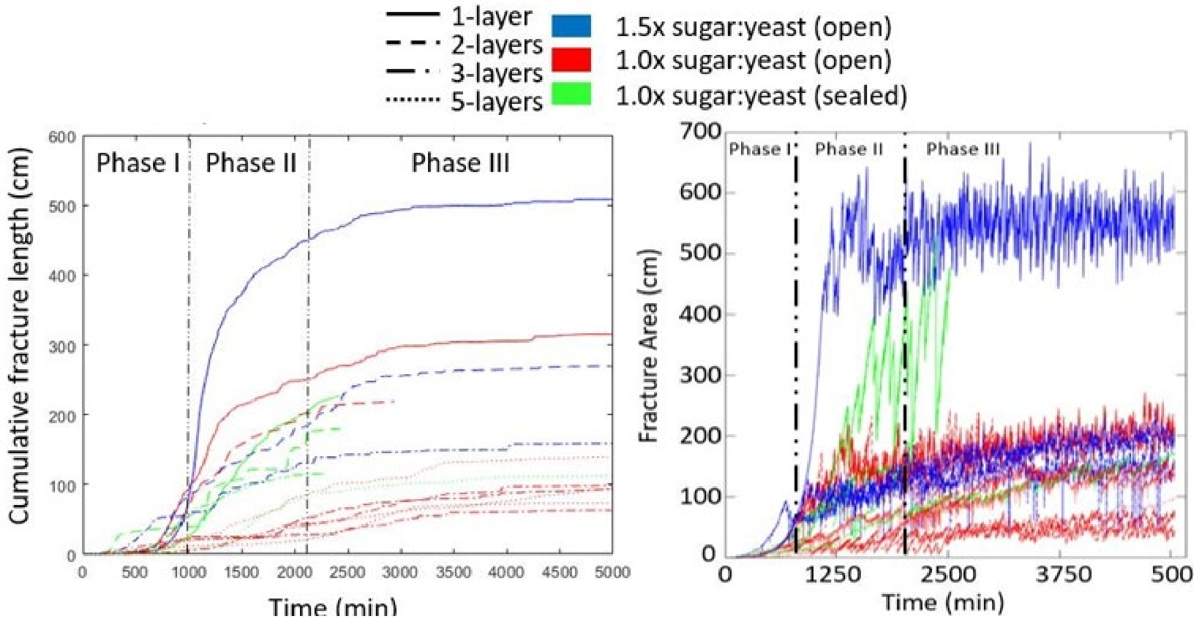


Figure 2 *– Fracture network creation over time in an analogue model (left) showing Phase I (diffusion and fracture creation), Phase II (fracture network interconnection), and Phase III (fluid expulsion). The fractured area stabilizes in Phase II during final fracture interconnection, and then varies within a given range in Phase III for each experiment as the fractures open and close during fluid expulsion.*

One model for expulsion is explored by Johnson et al., (2022c) wherein the process is originally driven by diffusion. However, low Φ-K relationships result in saturation and subsequently fracture propagation (Figure 2) driven by the largest kerogen lenses (Johnson et al., 2022b). With appropriate kerogen distribution within the shale this will create a fracture network that will open and close as pressure rises and falls (Johnson et al., 2022b; Johnson et. al., 2022c), allowing the periodic release of hydrocarbons (Figure 2).

Movement of hydrocarbons within the subsurface are driven by buoyancy, gravitational, and capillary forces. At the most basic level, the pathways are determined by Φ-K relationships via geological composition and structural elements (e.g. fractures, faults) (Wangen, 1995; Manzocchi et al., 2010). Hydrocarbons are geochemically reasonably stable, drastically reducing the potential interactions during migration (Price, 1993).

Initial projects for CO_2 storage assumed little to no migration would occur (Ringrose et al., 2013), however pilot studies for CCS has shown this to be a faulty assumption (e.g. In-Salah, Snøhvit). Therefore it is necessary to consider not only primary, but secondary seals in addition to possible migration pathways (Johnson et al., 2022a). Unlike hydrocarbons, CO_2 can be incredibly reactive when in the presence of the appropriate mineralogy. Busch et al., (2016) highlighted that CO_2 can be especially reactive with smectite resulting in volumes changes associated with fracture creation. While the injection of CO_2 does carry risk with it including seismic/aseismic fault slip, seal/trap integrity damage, and uplift/subsidence (Rutqvist, 2012). However, in the case of CO_2 escape from the primary reservoir the worst case scenario for CO_2 migration is that it is re-released into the atmosphere after a tortuous journey through the subsurface. This does however highlight the need for surface monitoring at all CCS wellsites.

Reservoir

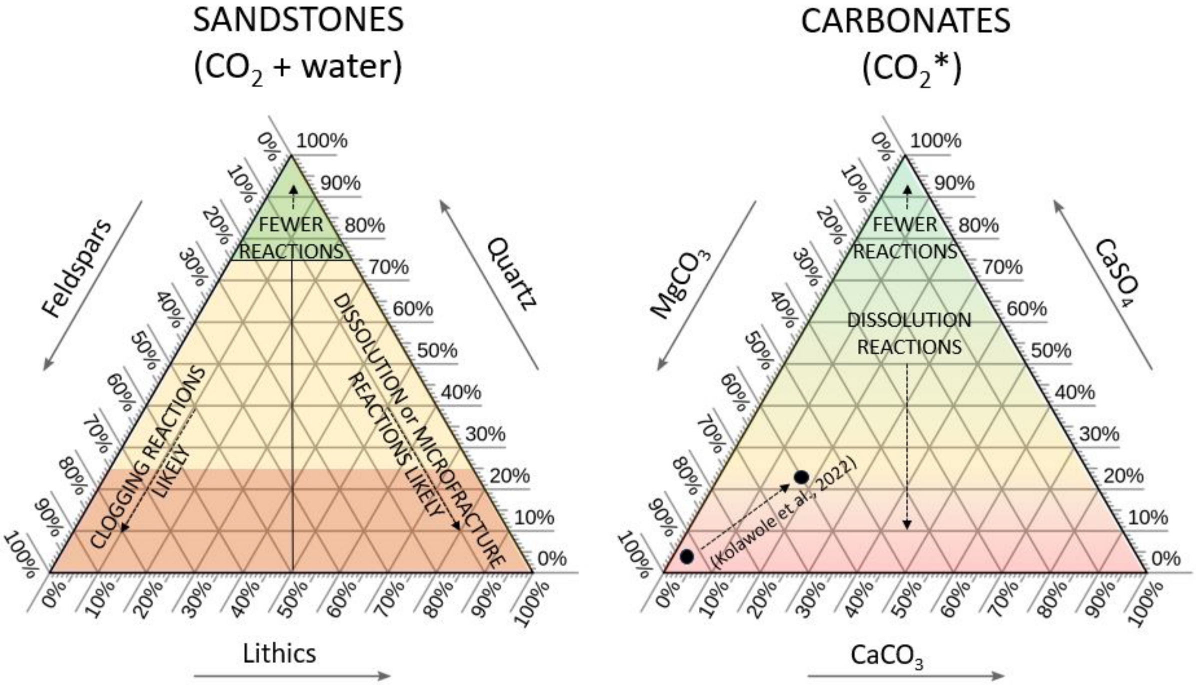
There is a long history within hydrocarbon exploration of targeting primarily two reservoir types (i.e. sandstones, carbonates). Worldwide, the ratio of sandstone to carbonate reservoirs are 3:2 (Bjørlykke and Jahren, 2010) while the distribution of total hydrocarbons in sandstone reservoirs is closer to ~50% (SLB, 2024).

Similarly, both sandstone and carbonate reservoirs have been considered and utilized for CO_2 storage pilot projects (i.e. <1 Mt /yr). Since CO_2 is geochemically reactive, larger projects have favoured sandstone reservoirs preferably composed dominantly by quartz (Figure 3). Deviations from this encourage geochemical reactions including, but not limited to (Hangx and Spiers, 2009):

$$CaAl_2Si_sO_8 + CO_2 + 2H_2O \rightarrow\ CaCO_3 +\ Al_2Si_2O_5(OH)_4 \tag{1}$$

$$NaAlSi_sO_8 + CO_2 + H_2O \rightarrow NaAl(CO_3)(OH)_2 + 3\,SiO_2 \tag{2}$$

The potential problem with numerous geochemical reactions is that it greatly increases uncertainty, including increased potential for complications as a result of injection as outlined by Rutqvist (2012). For example a feldspar rich sandstone could see a reaction similar to Equation 1, in which anorthite goes to $CaCO_3$ and kaolinite in the presence of CO_2 and water. $CaCO_3$ will likely react further (see Equation 3) while the presence of kaolinite will likely clog the pore space.



*In the presence of water, and appropriate reservoir conditions (c. 900-1200m depth) anhydrite can react to become gypsum creating microfractures

Figure 3 *– Shows less reactive regions of mineralogical content of a sandstone (left) and carbonate (right) reservoir given current understanding of geochemical reactions between CO_2 and minerals commonly present within these reservoir types. On the sandstone ternary diagram the presence of water is also considered. On the carbonate ternary diagram, the impact of introducing Sporosarcina pasteurii on the mineralogical content is highlighted based on work by Kolawole et al., (2022).*

Carbonate reservoirs have been considered especially problematic as most carbonate minerals readily react with CO_2. For example (Campbell et al., 2022):

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- \tag{3}$$

$$CaMg(CO_3)_2 + 2CO_2 + 2H_2O \rightarrow Mg^{2+} + Ca^{2+} + 4HCO_3^- \tag{4}$$

It has been established that these alterations can lead to dissolution within the reservoir, encouraging mechanical weakness (Seyyedi et al., 2020). However, many sedimentary basins do not have an abundance of clean quartz reservoirs and may at least partially rely upon the use of carbonate reservoirs for their CCS opportunities (e.g. Western Canadian Sedimentary Basin, Central Arabic Basin). To this end, early research has shown that there are potential pathways forward (Kolawole et al., 2022). For example, injecting a preparation fluid into a carbonate reservoir can significantly alter the geochemistry in such a way that it would be more ready to receive CO_2 (Figure 3).

In the case of all reservoirs for CCS, it is important to consider when CO_2 becomes supercritical. At approximately 800m depth, CO2 has been shown to become supercritical, although this can vary somewhat depending on local PT regime. When CO_2 becomes supercritical the amount of CO_2 that you can fit into a given space is both significantly improved, as well optimized. Roughly

800m is considered optimal since the further improvement for storage capacity between approximately 800m and 3000m depth is 0.05% compared to the compression that has already occurred during the first 800m (DOE, 2024). Wang et al., (2018) has shown that cooler basins will result in greater CO_2 density as pressure and depth increase.

Seal/Trap

When considering potential seals/traps for hydrocarbons there are a variety of geometries that could potentially work, however the most commonly used and the safest are 4-way closures and 3-way closures (SPE, 2024). 4-way closures depend entirely on the shape of the seal in combination with an appropriate Φ-K relationship (i.e. low Φ, low K). 3-way closures are more complex in that they further depend on a large-scale structural element (i.e. fault) and the compositional relationships across them (Yielding et al., 2010). The classic relationship shows the importance of these compositional relationships. However, it goes on to explain that this can be further complicated by the sealing or non-sealing nature of the fault gouge itself (Yielding et al., 2010; Vrolijk et al., 2016). This is another field of research within which there is an active and ongoing debate (Smith, 1966; Yielding et al., 2010; Vrolijk et al., 2016).

For CO_2, we have already touched on the potential for geochemical reactions and how that might adversely affect a potential seal. Therefore, a focus will be applied on understanding the long-term advantages and disadvantages of these potential seal/trap types. Since 3-way closures depend on a sealing-fault, and subsurface systems are dynamic especially when interacted with, they present a greater risk than 4-way closures. However, most if not all basins have undergone some major structural changes via tectonic forces resulting in the need to consider more complex geometries frequently (e.g. WCSB, Norwegian Continental Shelf).

Due to the comparable size and attributes of CH_4 and CO_2, it could be argued that hydrocarbon reservoirs that have had supercritical CH_4 have ‘tested capacity’, while saline aquifers do not. Indeed, where this is the case and space has been made available these areas should be primary targets for permanent CO_2 storage. However, due to the limited amount of space available in all hydrocarbon reservoirs, not just the ones that had supercritical CO_2, it will be necessary to utilize saline aquifers (Anthonsen et al., 2013). Nonetheless, understanding the characteristics of traps/seals that held supercritical CH_4 may provide the greatest learnings for future CO_2 reservoirs.

Conclusions

Here we have utilized the same elements of a hydrocarbon system to look at the components of CO_2 systems, and the different kinds of complexity that are associated with a change in fluid in combination with a change in direction of fluid flow. The development of larger scale CO_2 projects are and should develop from the simplest combination of these elements (e.g. Sleipner, Quest). However, the shear size of the problem demands innovation that will allow more complex CO_2 systems to be harnessed. Complex sourcing (e.g. DACs), complex migration (multiple seals), complex reservoirs (e.g. carbonates, arkose, lithic), and complex seal/trap sequences should be viewed as necessary scientific challenges in order to dispose of the anthropogenically created waste product (i.e. CO_2).

Acknowledgements

We would like to acknowledge Forskningsrådet for grant #331644 (NCS2030) for their support.

References

Anthonsen, K., Ågard, P., Bergmo, P., Erlstrom, M., Fareide, J., Gislason, S., Mortensen, G., and Snæbjørnsdottir, S., 2013, CO2 storage potential in the Nordic region, Energy Procedia, 37, 5080-5092

Bjølykke, K., and Jahren, J., 2010, Sandstones and Sandstone Reservoirs in Petroleum Geoscience, pgs. 113-140

Busch, A., Bertier, P., Gensterblum, Y., Rother, G., Spiers, C.J., Zhang, M., Wentinck, H.M., 2016, On sorption and swelling of CO2 in clays, Geomechanics, Geophysics, Geoengineering, and Georesources, 2, 111-130

Campbell, J.S., Foteinis, S., Furey, V., Hawrot, O., Pike, D., Aeschlimaan, S., Maesano, C.N., Reginato, P.L., Goodwin, D.R., Looger, L.L., Boyden, E.S., and Renforth, P., 2022, Geochemical negative emissions technologies: Part I. Review, Frontiers in Climate

Cooke, I.L., 2014, User guide total organic carbon (TOC) dataset: British Geological Survey (BGS) internal report.

DOE, 2024, USA Department of Energy, https://netl.doe.gov/carbon-storage/, accessed January 2024

DNV, 2024, Det Norske Veritas, https://www.dnv.com/, accessed February 2024

Gretener, P.E., and Curtis, C.D., 1982, Role of temperature and time on organic metamorphism: Geologic Notes, AAPG Bulletin, 66, 8, 1124-1129

Hangx, S.J.T., and Spiers, C.J., 2009, Reaction of plagioclase feldspars with CO2 under hydrothermal conditions, Chemical Geology, 265, 1-2, 88-98

Johnson, J.R., Hansen, J.A., Rahman, J., Renard, F., and Mondol, N.H., 2022a. Mapping the maturity of organic-rich shale with combined geochemical and geophysical data, Draupne Formation, Norwegian Continental Shelf, Marine and Petroleum Geology, 138, 105525

Johnson, J.R., Kobchenko, M., Mondol, N.H., and Renard, F., 2022b, Multiscale synchrotron microtomography imaging of kerogen lenses in organic-rich shales from the Norwegian Continental Shelf. International Journal of Coal Geology, 253, 103954

Johnson, J.R., Kobchenko, M., Johnson, A.C., Mondol, N.H., and Renard, F., 2022c, Experimental modelling of primary migration in a layered, brittle analogue system, Tectonophysics, 840, 229575

Kobchenko, M., Panahi, H., Renard, F., Dysthe, D.K., Malthe-Sorenssen, A., Mazzini, A., Scheibert, J., Jamtveit, B., Meakin, P., 2014, Fracturing controlled primary migration of hydrocarbon fluids during heating of organic-rich shales, HAL open science

Kolawole, O., Millikan, C., Kumar, M., Ispas, I., Schartz, B., Weber, J., Badurina, L., Segvic, B., 2022, Impact of microbial-rock-CO2 interactions on containment and storage security of supercritical CO2 in carbonates. International Journal of Greenhouse Gas Control, 120, 103755

LSE, 2024, London School of Economics, Grantham Research Institute on Climate Change and the Environment, https://lse.ac.uk/granthaminstitute/, accessed February 2024

Manzocchi, T., Childs, C., and Walsh, J.J., 2010, Faults and fault properties in hydrocarbon flow models, Geofluids, 10, 94-113

Price, L., 2013, Thermal stability of hydrocarbons in nature: Limits, evidence, characteristics, and possible controls, Geochimica et Cosmochimica Acta, 57, 14, 3261-3280

Ringrose, P.S., Mathieson, A.S., Wright, I.W., Selama, F., Hansen, O., Bissell, R., Saoula, N., Midgley, J., 2013. The In Salah CO2 storage project: Lessons learned and knowledge transfer, Energy Procedia, 37, 6226-6236

Rutqvist, J., 2012, The geomechanics of CO2 storage in deep sedimentary formations, Geotechnical and Geological Engineering, 30, 525-551

Seyyedi, M., Mahmud, H.K.B., Verrall, M., Giwelli, A., Esteban, L., Ghasemiziarani, M., Clennell, B., 2020, Pore structure changes occur during CO2 injection into carbonate reservoirs, Nature Scientific Reports, 10, 3624

Smith, D.A., 1966, Theoretical considerations of sealing and non-sealing faults, AAPG Bulletin, 50, 2, 363-374

SLB, 2024, Schlumberger Limited, https://www.slb.com/, accessed February 2024

SPE, 2024, Society of Petroleum Engineers, https://www.spe.org/, accessed January 2024

Statcan, 2024, Statistics Canada, https://www150.statcan.gc.ca/, accessed February 2024

Tissot, B.P., and Welte, D.H., 1984, Production and accumulation of Organic Matter, The Organic Carbon Cycle in Petroleum Formation and Occurence

Vrolijk, P.J., Urai, J.L., Ketterman, M., 2016, Clay smear: Review of mechanisms and applications, Journal of Structural Geology, 86, 95-152

Wang, J., Elsworth, D., Wu, Y., Liu, J., Zhu, W., and Liu, Y., 2018, The influence of fracturing fluids on fracturing processes: A comparison between water, oil, and SC-CO2, Rock Mechanics and Rock Engineering, 51, 299-313

Wangen, M., 1995, The blanketing effect in sedimentary basins, Basin Research, 7, 4, 283-298

Yielding,G., Bretan, P., and Freeman, B., 2010, Fault seal calibration, Geological Society London Special Publications, 347, 243-255