The Cretaceous Enigma on the NCS – some Thoughts on Migration Apsects and more on the Cretaceous Petroleum Systems (.?)

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Synopsis on what we learned from Reservoir Filling Studies

From about 90 filling direction/filling history studies – using geochemistry - over the last 30 years - Including previously - filled-now dry (PFND) traps, the following can be generalized:

- **Later migration distances** – seldom more than 20-30km, unless including effects of uplift induced remigration Mid-Norway/Haltenbanken, Ekofisk-region**, some exceptions** Siri-trend/Goliath. Trap Leakage- pseudo-steady-state – fault/seal/radial-faults
- Clear **directional "filling-geochem-trends**" in most large trap systems; Gullfaks, Snorre, Visund, Draugen, Heidrun, Norne-Svale, Skarv, Agat, Hild
- **Migration <u>up-fault</u>** – related to deep carrier systems is a most prolific model & more common on the NCS than the «Brae inter-fingering» shale-sand model; Smørbukk, Heidrun, Skrugard/Havis/Sleipner
- Most traps show **paleo-saturation of different types of oil** – in some cases (5) as old as Devonian – implying several Critical Moments; Agat region, Helgeland B., Ula, Embla
- Fennoscandian **uplift** (Miocene-Pliocene cf. Japsen et al. 2018) has caused remigration - big time
- However, uplift also generated oil-legs in traps which would previously have held much gas+some oil; Barents Sea, Albatross/Askeladden/Snøhvit/Troll – Victoria/Nyk High
- «Blends of oils» in traps is more common than not; Barents Sea, J. Sverdrup
- **Palaeobiodegradation** is common in traps – reflecting early/shallow initial fill; Ula/Hild/Skarv/Dvalin/Barents Sea/Stockman/Balder/Grane/Oseberg
- **Paleo-filling** means that less «new top-up» is needed to fill prospects e.g. Gohta/Skrugard
- **Cretaceous** oil and gas systems seems – somehow localized – «lack» of Clinoforms (commnet P.Varhaug)?
- **Cap rock properties** rather than SR type determine oil or gas in traps sourced from the Cretaceous
- Several traps – previously believed to hold Åre charge, are **rather filled** from Cretaceous

Cretaceous "Petroleum System

Until recently, Cretaceous derived oil, in Cretaceous or younger traps has been somewhat elusive on the NCS, and certainly not a focal point for major commercial interest nor discoveries, despite the occasional drill-cutting representing Cretaceous siliciclastic lamina type source rocks samples which, generally show good to very good source rock characteristics.

World-wide, the story is quite different with Cretaceous source rocks and reservoirs in particular in the temperate and paleo-Equatorial depositional systems like the La Luna in the west, and in the east, e.g. formed during the later stages of the Tethys collapse, where e.g. the Hanifa-Arab system represents deposited source rocks and reservoirs in carbonate platform settings with anoxic sub-basins, with a "Petroleum Machinery" dominated by the continued deposition of the various basin and sub-basin in the greater Zagros Fore-Deep.

Characteristic for these systems are Type II-S kerogens (resulting in low temp kerogen to oil transformation), deposited in physical close connection with carrier beds and reservoir units, huge growth anticlinals and gently sloping strata allowing for also long to ultra-long foreland-basin style migration. These systems are "notoriously" well connected with excellent basin scale plumbing characteristics and migration distances of several hundred km.
Field area size dominates over source rock-area. Migration patterns are simple in oil-wetting strata. Eternal flames caused by gas escape features on regional anticlinals, which allows oil to remain in traps by leaking off gas – cf. Sales III principles) formed the basis for the importance of fire in regional belief systems, like Zarathustrianism, and bitumen was used since the Neolithic in handcrafts and construction.

Thus, high productivity Mid-Late Cretaceous SRs are known from many regions *e.g.* from the Eastern Venezuela basin – a Type II SR yielding 27t of petroleum/m^2, the Kazhdumi Fm. in Iran – a Type II SR yielding 25t/m^2, the Mid Magdalena basin in Columbia – with a Type II SR yielding 16t/m^2, the Gulf of Suez in Egypt – with a Type II SR yielding 14t/m^2, the Maturin basin in Venezuela – a Type II SR yielding 12t/m^2, the Maracaibo basin in Venezuela – a Type II SR yielding 10t/m^2, the Orient basin in Ecuador – with a Type II SR yielding 5t/m^2 and the Tres Cruces basin in Argentina – a Type II SR yielding c. 1 t/m^2, to name a few. Thus, Cretaceous source rocks are world-wide "Petroleum machineries" ("S/O") of immense importance and recent Critical Moments contribute to their economic importance.

In this presentation we look into some "Petroleum System" aspects of the Boreal East-Atlantic Cretaceous - NCS, and in particular 5 oils known to be sourced from Cretaceous strata (age specific biomarkers) off Mid-Norway. We use these as proxies for source rocks. These oils include Ormen Lange 6305/8-1 MDT (Egga Fm 2.9km), 6406/5-1 DST (Springar Fm 2.6km), Ellida 6405/7-1 DST 1 (Nise Fm 2.8km), Marulk 6507/2-2 DST 2 (Lysing Fm 2.8km), and Snefrid 6706/12-2 (Nise Fm 2.6km). As we have hence proven oil of Cretaceous origin to exist, the Cretaceous "Oil Machinery (!)" on the NCS is thus proven, and one might ask what is then the problem – wherein lies the enigma?

Our oils represent generation from shales of several different Cretaceous ages ("S/O"), in fact the whole Cretaceous as judged "literally" by the nordiacholestanes, but none of these rocks have been proven by drilling in recognizable massive occurrences. Their existence is thus – still elusive and inferred based on the oils. However, generation of sufficient quantities of mature oil to allow expulsion, primary and secondary migration, given the loss factors, means that massive source rocks must exist in the drainage area of our wells with the associated oils.

One question begs an answer; why have the source rocks not been drilled, and why do these oils and associated source rocks not occur in more places? Why not bigger volumes of oil? Some will point to the general lack of clinoforms in the Vøring Basin and associated regions i.e. we have a "plumbing/drainage-problem". Still, the fact that our 5 petroleum samples are oils and condensates, implies that also large volumes of gas must have been generated. Where is it? In the trap like for Ormen - yes possibly, but where is the gas in case of the other oils and condensates. Do we recognize this gas? Are some of our Jurassic oils in fact Cretaceous? Do we miss out on something here "O"? Are in fact most of the Vøring Region discoveries also holding Cretaceous derived gas, despite some of them clearly containing oil-type petroleum inclusions – believed by us to be Jurassic? Was this wrong? In that case, what are the implications ("O")?

Particular to our 5 "undisputed" Cretaceous oils are relatively high Pr/Ph values, variable input of specific terrestrial higher plant components, while the stable carbon isotope values vary greatly, and the biomarkers suggest clearly dominantly marine Type II/III kerogens formation in dysoxic/anoxic marine sub-basins. Apart from this are the oils at first sight – "boringly-normal-marine" and could pass of as e.g. Jurassic. Indeed we have several candidates in the region, previously believed to be Jurassic derived petroleums. It is likely that migration was laterally mostly comparatively short range into stratigraphic traps, or late formed structural traps, but the oils are all mature i.e. from greater depths proving migration on faults i.e. significant vertical vectors ("S"), but the associated petroleum flow is thus "concentrated" and not occurring on a "broad front".

It is the aim of this project and a follow up "consortium-company-project" designed to examine in more detail the paleo-depositional conditions of the source rock systems that generated these oils in relation to stratigraphy, tectonic setting and climatic oceanic-sea temperature variations through the Cretaceous, to better understand the limiting factors to the paleo-depositional source rock environment and also the primary productivity along the NCS. As of yet this all is poorly understood.

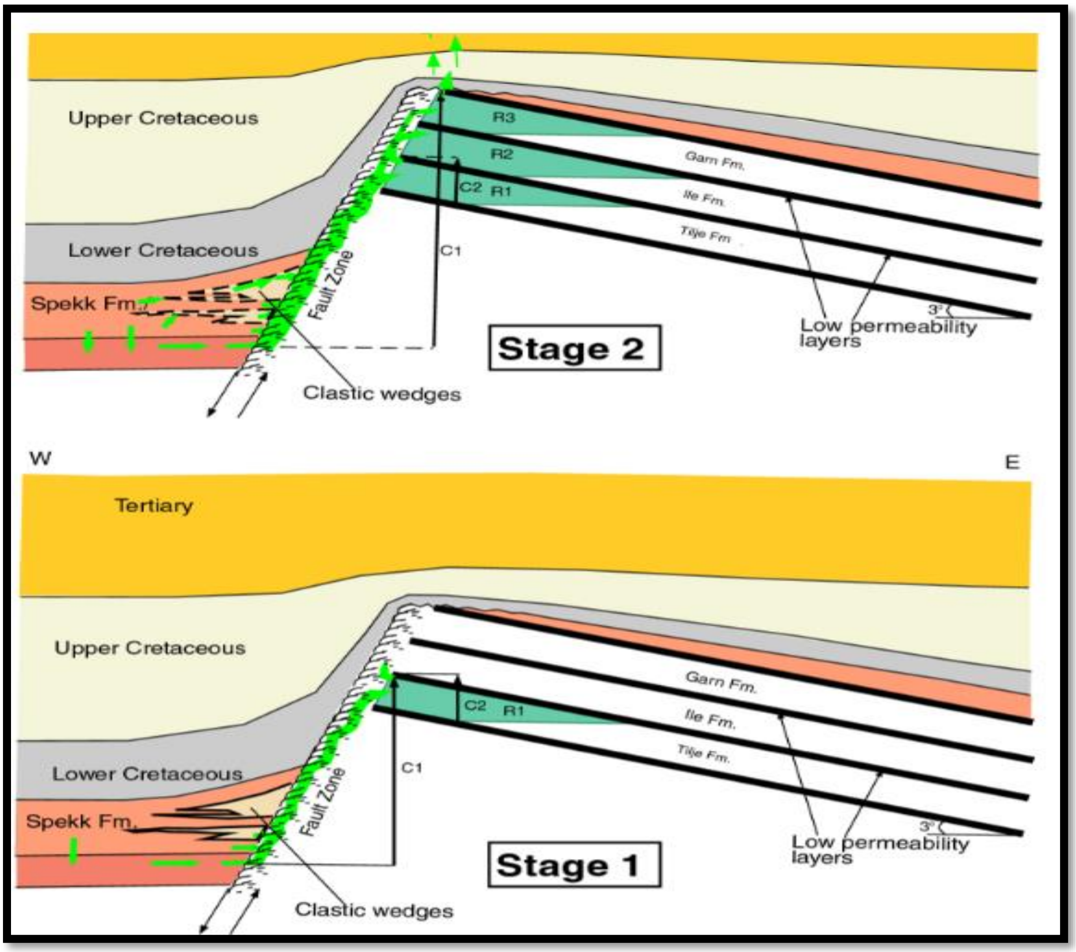
While more concentrated massive Cretaceous source rocks has been reported recently in the Barents Sea, and also from onshore Greenland, and while Cretaceous shale lamina with high TOC and HI values are known from the NCS, in particular from cuttings, it seems generally that rapid sedimentation and dilution of the Cretaceous OM represents a risk factor in many setting ("T". Such sedimentation, and the rapid subsidence of the Late Cretaceous and Tertiary strata e.g. as noted in the notorious Vestbakken well (7316/5-1) – a situation with "text book" generation profiles from finely dispersed OM, but lack of concentrated source rocks, hence early expulsion of liquid HC will suffer relative to gas generation, but the well shows that organic productivity was high (also cf. the coals in Svalbard), and dilution is likely to represents both "W" and "T".

It is thus possible that sub-basin with more shielded sedimentation rates would represents better paleo-source rock machineries, and possibly systems shielded from any cold polar-derived oxygenated deep water currents. Such systems exist on the shelf in relation to the complex patterns of sea-floor spreading. It is also possible that the overpressure development in Cretaceous and Tertiary strata acted to limit migration of Jurassic derive petroleum into trap systems, rendering these and the migration avenues "dry" until local "in-situ" Cretaceous petroleum production took hold, resulting in high migration loss factors ("W/T").

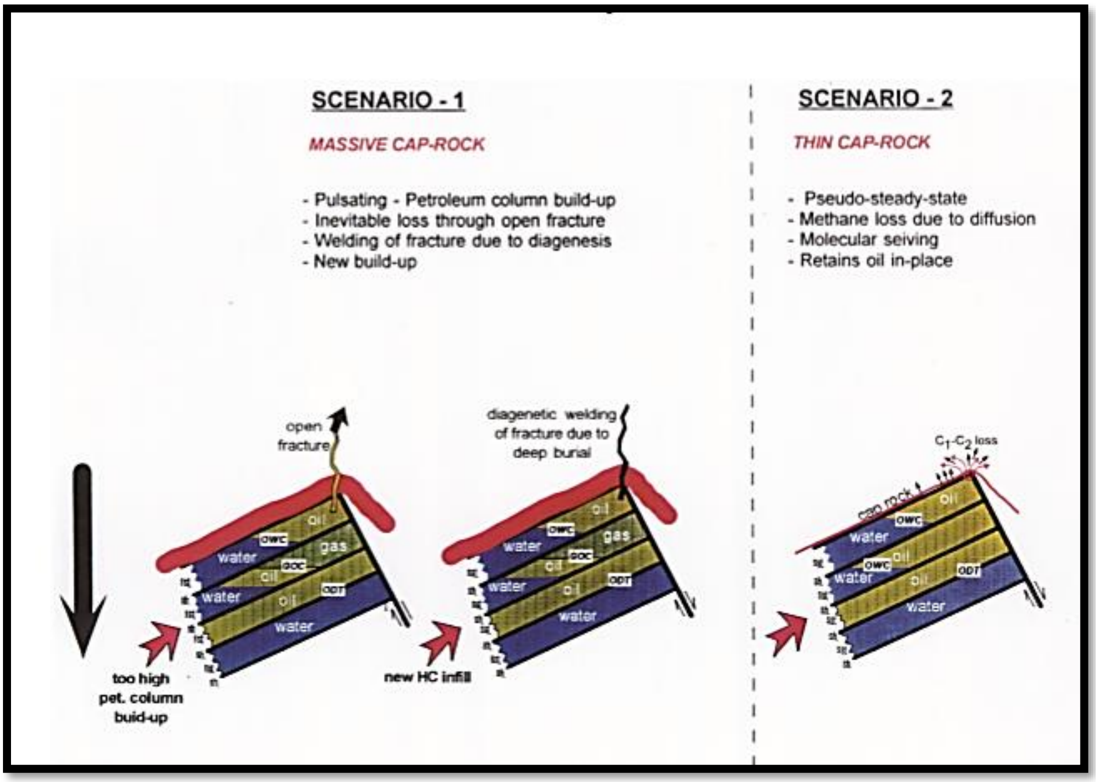
Contrary to this did the Jurassic trap systems benefit from paleo-migration building oil saturation in the deep regional high-way systems of the Statfjord Gp, with oil saturating migration pathways from a multitude of older source rocks, including Devonian, Triassic, Jurassic (coal and shales). Faults interconnecting the deep migration system with Jurassic fault-traps secured effective trap filling, and in particular are the leaking trap systems like Ekofisk, Johan Sverdrup, Oseberg, Statfjord, Gullfaks, Njord, Norne, Goliath and Alta/Gohta, manifestations of the importance of the Sales III traps to prolific commercial oil exploration in both subsiding, and uplifted basins.

It is possible that the Cretaceous stratigraphic traps are generally too limited in size, and that the late tectonic traps are too tight ("W/T") i.e. Sales I category for these trap system to be major oil accumulations. However, faulted and fractures cap-rocks of traps in the uplifted Barents Sea, i.e. traps with partly leaking cap rocks could benefit from the kinetic energy of gas allowing for a second force for migration, and a way to selectively "bleed off" gas while retaining oil ("S"/O").

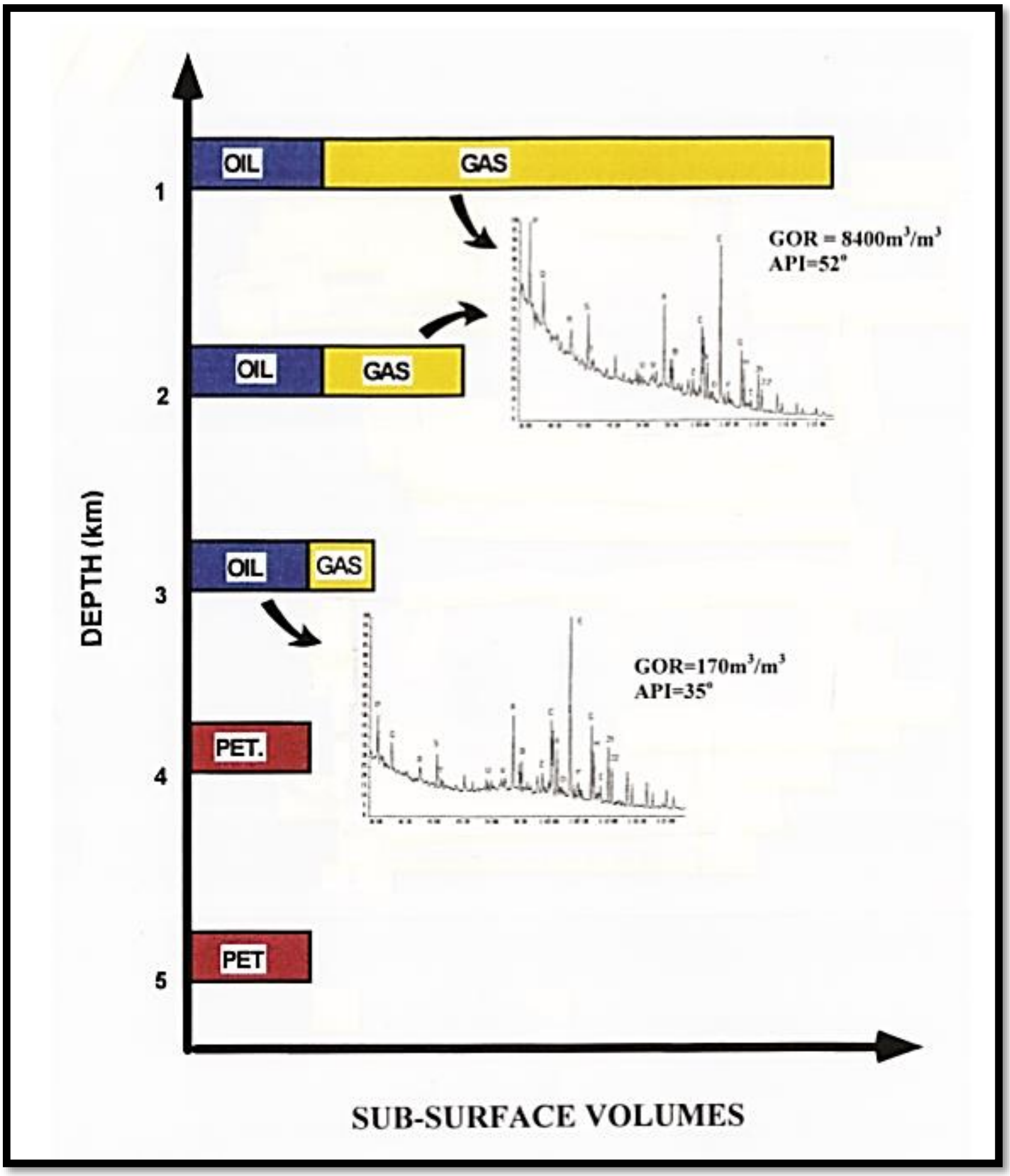
Off Mid-Norway, Cretaceous traps in connection with faults would in the same way provide interesting targets ("O"), and it is far too early to "down-play" the exploration potential of the Cretaceous source rock systems.



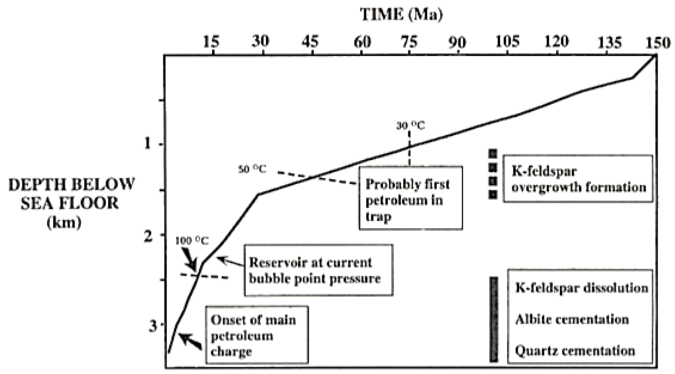
Migration up-faults is more common than generally assumed. Traps may fill "bottom-up" and not
top-down as commonly assumed. Model originally developed from Smørbukk – Halten Terrace.
(Karlsen et al., 2004; Karlsen and Skeie, 2006). Model later found to be generally applicable, also
in regional perspectives.

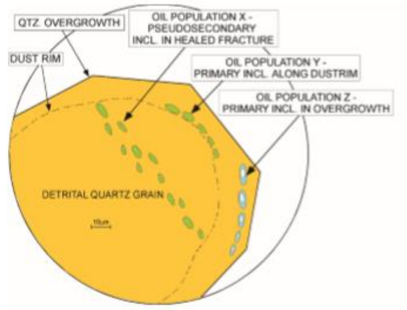


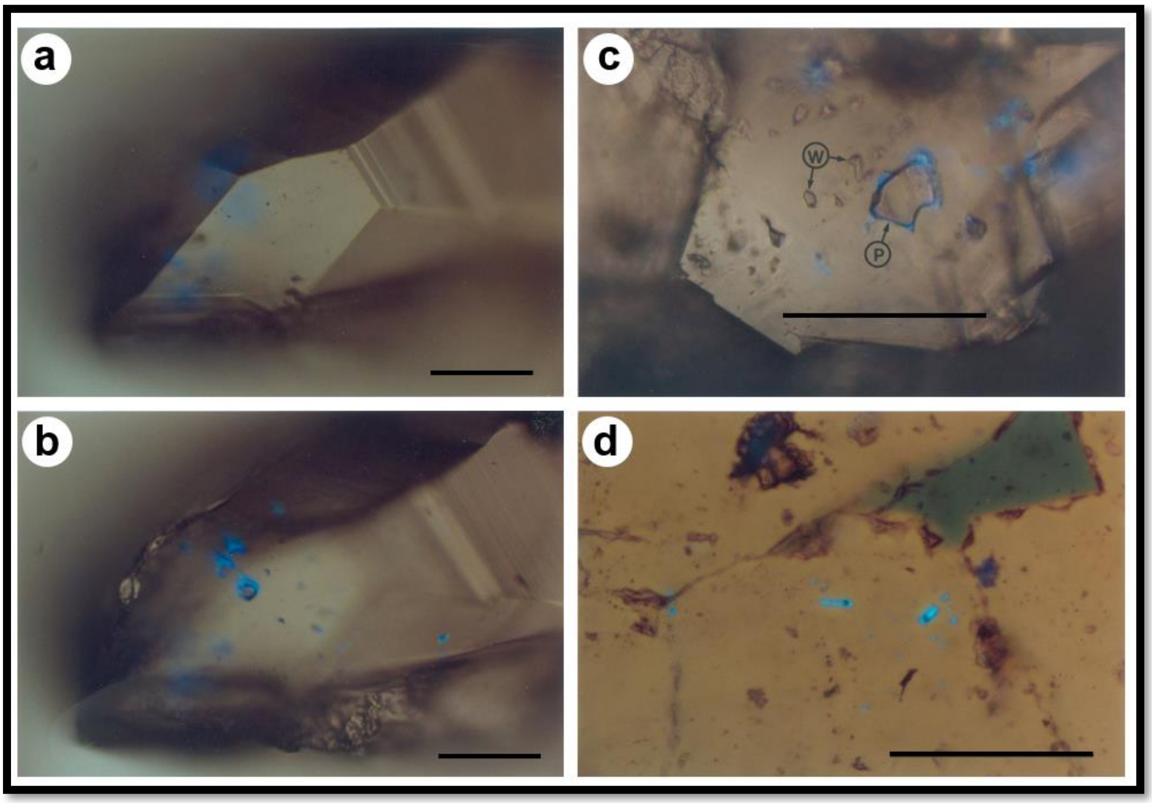
Cap rock properties are found to be generally dominant in determining GOR in traps, and far more important the conventional factors. (Karlsen et al., 2004; Karlsen and Skeie, 2006).



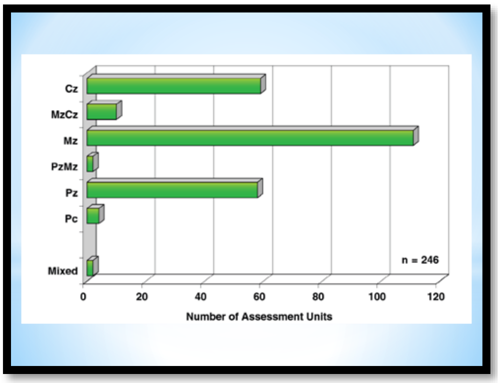
Massive errors are committed in interpretations of geochemical data because people do not consider
the effects of PVT on molecular ratios for facies- and maturity-parameters.
The same can be said about the effects of biodegradation. (Karlsen et al., 2004; Karlsen and Skeie, 2006).

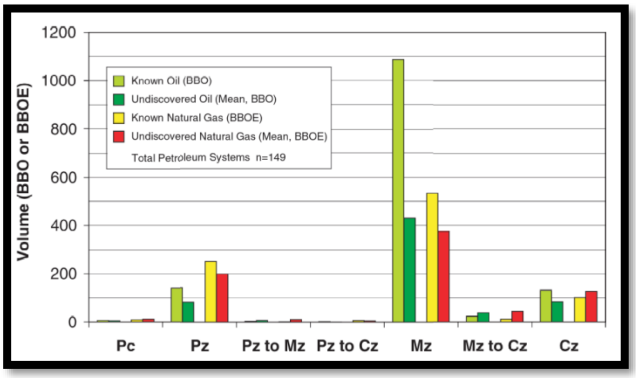




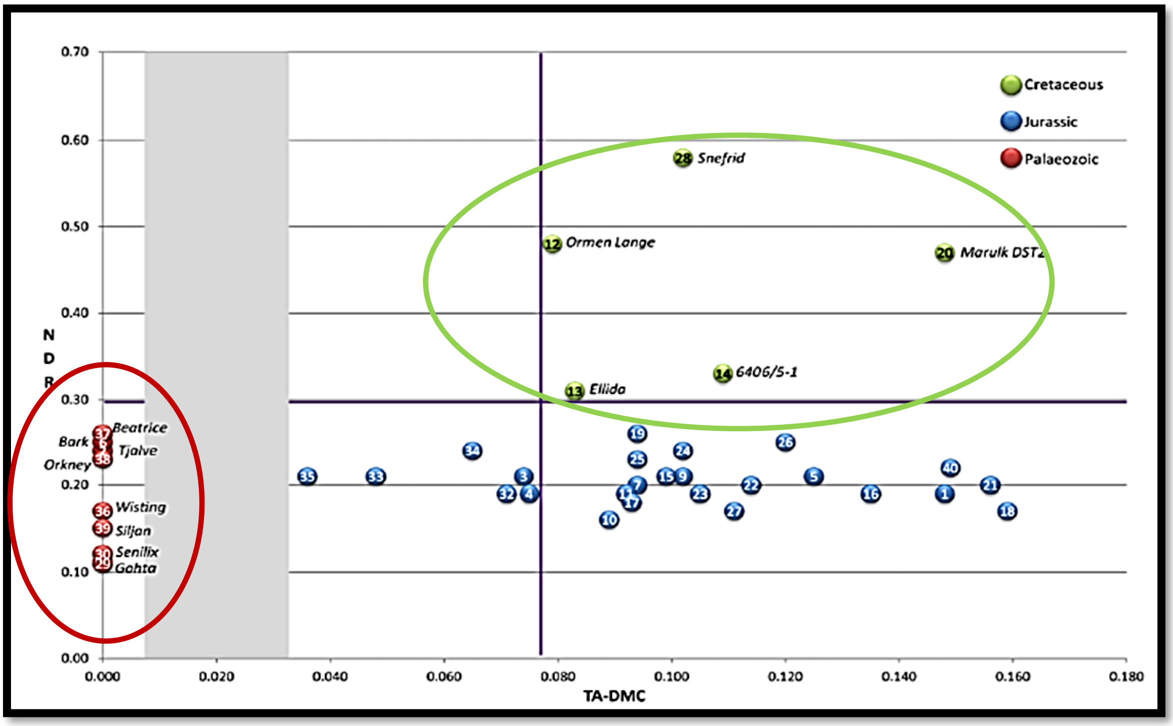


Petroleum inclusions is diagenetic minerals continues (since Karlsen et al., 1993) to be a major tool for deciphering "filling-histories" and "basin-scale" migration trends.





Why "young, good and rich" is generally, world-wide better than "old, bad and poor"- assessment units of Petroleum Systems around the world underlining the importance of the Jurassic and Cretaceous Petroelum systems (from Ahlbrandt et al., 2005, AAPG Mem,86). These are both superior in size, quality and with reasonable "Critical Moments" i.e. relatively short preservation potententails are needed for the "Petroleum Machinery" to work today. Critical application of the paramters is related to problems of "biomarker pick-up" in reservoires or migration avenues (a major challenge in Cretaceous reservoares "T"), blending of petroleum in traps, and alteration effects of the parameters (biodegradation/PVT-effects). It is clear that much more work is needed on the NCS before we understand fully the dymamics of the petroleum systems, and berfore we attain a better process understanding of the Cretaceous, and our petroleum inclusion technology continues to shed light on the multi-faceted problem scenario concerning the interplay between Cretaceous source rocks, generation from Cretaceous strata and entrappment in Cretaceous/Tertiary traps.



The advance in taxa-specific age specific biomarkers has allowed for a much better age-identification of oils in relation to source rocks, in particular of marine source rocks. This is in the Mesozoic related to intensive sea floor spreading and generation of more coastlines and thus ecological niches. (Matapour and Karlsen, 2018).

Still, compounds like betacarotane and oleanane still help in identifying lacustrine source rock facies, and higher plants (e.g. Tertiary delta- related oils), respectively, with e.g. gammacerane reflect hypersalinity/saline-lacustrine facies, and Ni/V of porphyrins help greatly in determining fresh water versus marine paleo-source rock settings (from Matapour & Karlsen, 2017).