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Cuttings and Mud gas data: A new perspective for Caprock Leakage in the North Sea

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ABSTRACT

Prior to contemporary times, direct hydrocarbon indicators (DHIs) such as stains, shows and seeps including mud gas and cuttings gas data had been used for the evaluation of potential hydrocarbon accumulations, maturation and productivity of source rock. Caprock leakage had never been viewed with greater interest than sparingly using these indicators. Modern studies have evolved into employing petrophysics of the caprock section, seismic sections and molecular geochemistry to discern potential mechanism and migration pathways of leaked petroleum via caprocks. In this study, thermogenic wet gas – depth profiles and thermogenic signature – depth profiles derived from cuttings (headspace)/or mud gas data show significant potential as a fast and reliable tool for evaluation of caprock leakage in the North Sea. The study showed that most wells in the North Sea have appreciable amounts of thermogenic wet gas in significant range of caprock sections above the caprock–reservoir interface over petroleum reservoirs, these observations infers leakage and the leaked hydrocarbons could have been delivered into the caprock sections via pressure prone fracture and capillary leakage through network of pores in the matrix of the caprocks.

Keywords: caprock, leakage, migration, reservoir, pore pressure.

INTRODUCTION

Environmental concerns such as the capture, storage and sequestration of CO_2, risking petroleum leakage which are an integral part of petroleum exploration, has brought petroleum caprock into a popular focus. Caprock, a fundamental imperative element of a petroleum system has a sole responsibility of preservation of accumulation in a trap. Caprocks, attracting significant attention in the storage and sequestration of CO_2 in depleted petroleum reservoirs, has earned a wide horizon of studies, i.e. Abrams (1996; 2005) on distribution of petroleum on the subsurface, Aplin & Larter (2005) on mud–rock properties, Clayton & Dando (1996) on rate of leakage, Clayton *et al.* (1997) on alteration during leakage, Fisher *et al.* (2001), Ingram & Urai (1999), Leith *et al.* (1993) on top seal, capillary and fracture leakages, Ligtenberg & Connolly (2003) on gas clouds and sealing quality, Nordgard Bolas & Hemanrud (2002, 2003) on leakage and retention capacities, Zieglar (1992) and Sales (1997) on buoyancy pressures and seal efficiency.

Previously cuttings and mud gas data were used to evaluate the maturity and productive capacity of corresponding formations and in most cases as indicators of petroleum accumulations (Thrasher *et al*., 1996). Concurrently, in then times caprock studies did sparingly employed the use of direct hydrocarbon indicators (DHIs) such as oil stains, oil shows and seeps, though recently, gas clouds in the crest of fields in seismic sections has been explored as a tool for evaluation of caprock leakage. However, modern developments show that cuttings and mud gas data can be used to discern the potential mechanism and migration pathways of leaked petroleum in petroleum caprocks. Nonetheless, the hypothesis on which this study rests is that the occurrence of thermogenic petroleum (obtained form cuttings and mud gas data) in immature formations (caprocks) overlying petroleum reservoirs, infers leakage of the caprock or migration of petroleum from the reservoir into the caprocks.

The principal components of natural gas are biogenic and thermogenic gases. Biogenic gas consists methane from immature organic matter and lignites, while thermogenic gas contains methane, ethane, propane, butane and sometimes pentane from mature organic matter. Thermogenic wet gas refers to ethane, propane and butane components (C_2–C_4) of the thermogenic gas and is normally expressed as %wetness $((C_2–C_4)/C_1–C_4)*100)$. In this study, thermogenic wet gas – depth profile (TGD) in corroboration with thermogenic signature – depth profile (TSD) and the vitrinite reflectance of the formations is presented as a fast, reliable, diagnostic indicator of caprock leakage in the North Sea on the premise that the presence of thermogenic wet gas in immature caprock sections overlying petroleum reservoir implies caprock leakage. The log view profiles were modelled with Techlog 2007.3 while the formations were modelled using Genesis 4.8.

Data source

Data for this study – which is an integral part of a greater study – were sourced from well completion reports, evaluation reports, composite logs and general information folios in the Norwegian Petroleum Directorate, Public domain and a study report by BP spanning across 50 wells in 41 oil fields in the UK and Norwegian Sectors of the North Sea (Figure 1). The choice of wells depended on availability of data on immature caprocks. Data types consist of mud /or cuttings (headspace) gas data (compositional data), isotopic data, pore pressure data expressed as EMW (Equivalent mud weight), organic matter maturation data and general geological information such as reservoir fluid types.

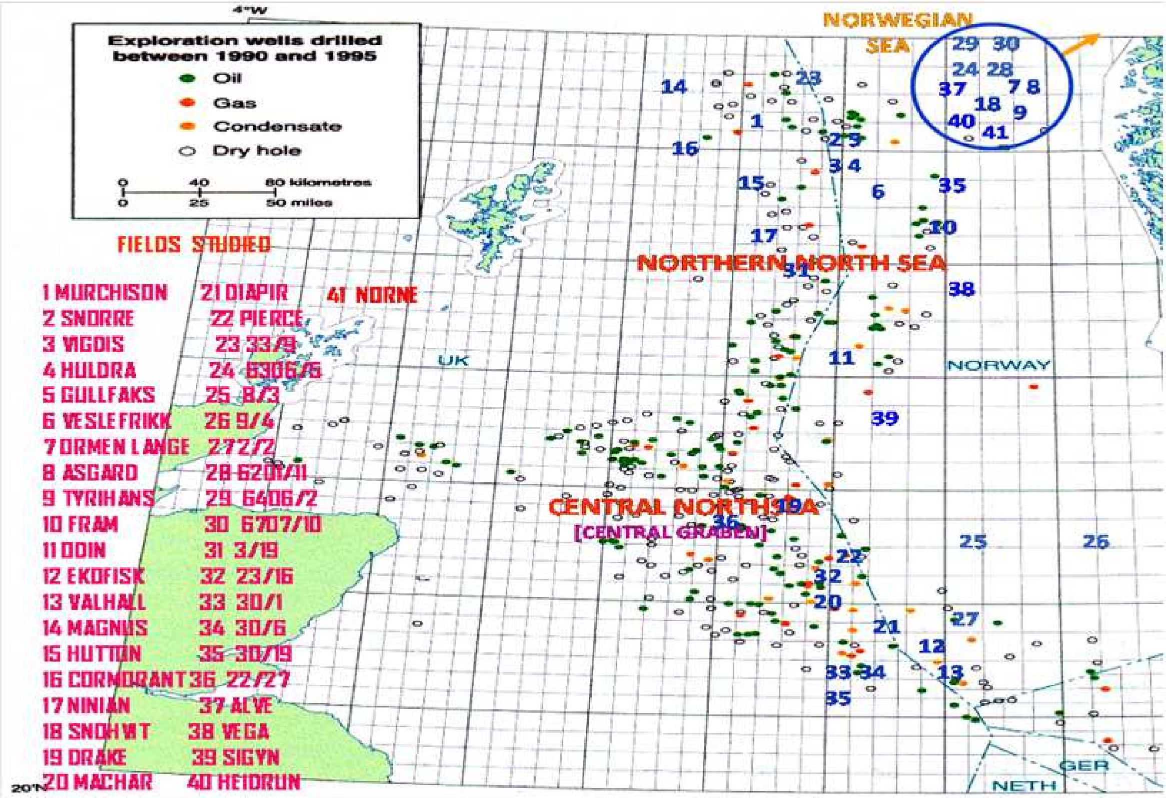

Figure 1 The map shows approximate locations of the oil field studied (Evans *et al.*, 2003).

RESULTS

Log view plots of thermogenic wet gas – depth (TGD) and thermogenic signature – depth (TSD) profiles and wet gas heights above reservoir–caprock interface for various wells are in figures 2 and 3. These plots also indicate the migration front (MF) of the wet gas, which also signifies the boundary between the leaking thermogenic gas from the reservoir and the biogenic gas generated by immature organic matter and shallow lignites. The evaluation of the presence of thermogenic wet gas in caprocks was performed based on profiles obtained for which thermogenic wet gas ($C_2 – C_4$) was quantified as percentages of the total hydrocarbon ($C_1 – C_4$) while the thermogenic signature (iC_4/nC_4) was applied as a check to the limit for occurrence of mature thermogenic wet gas and an aid to detect the thermogenic – biogenic gas boundary for which the ratio does not exceed 1.0. These were carefully used as a guide to establish the migratory petroleum front (MF). However, it was observed that in most cases the thermogenic wet gas threshold (5%) corresponded to the limiting value for the iC_4/nC_4 ratio, which indicate major consistent shift towards higher value (1.0) corresponding to the migratory petroleum front.

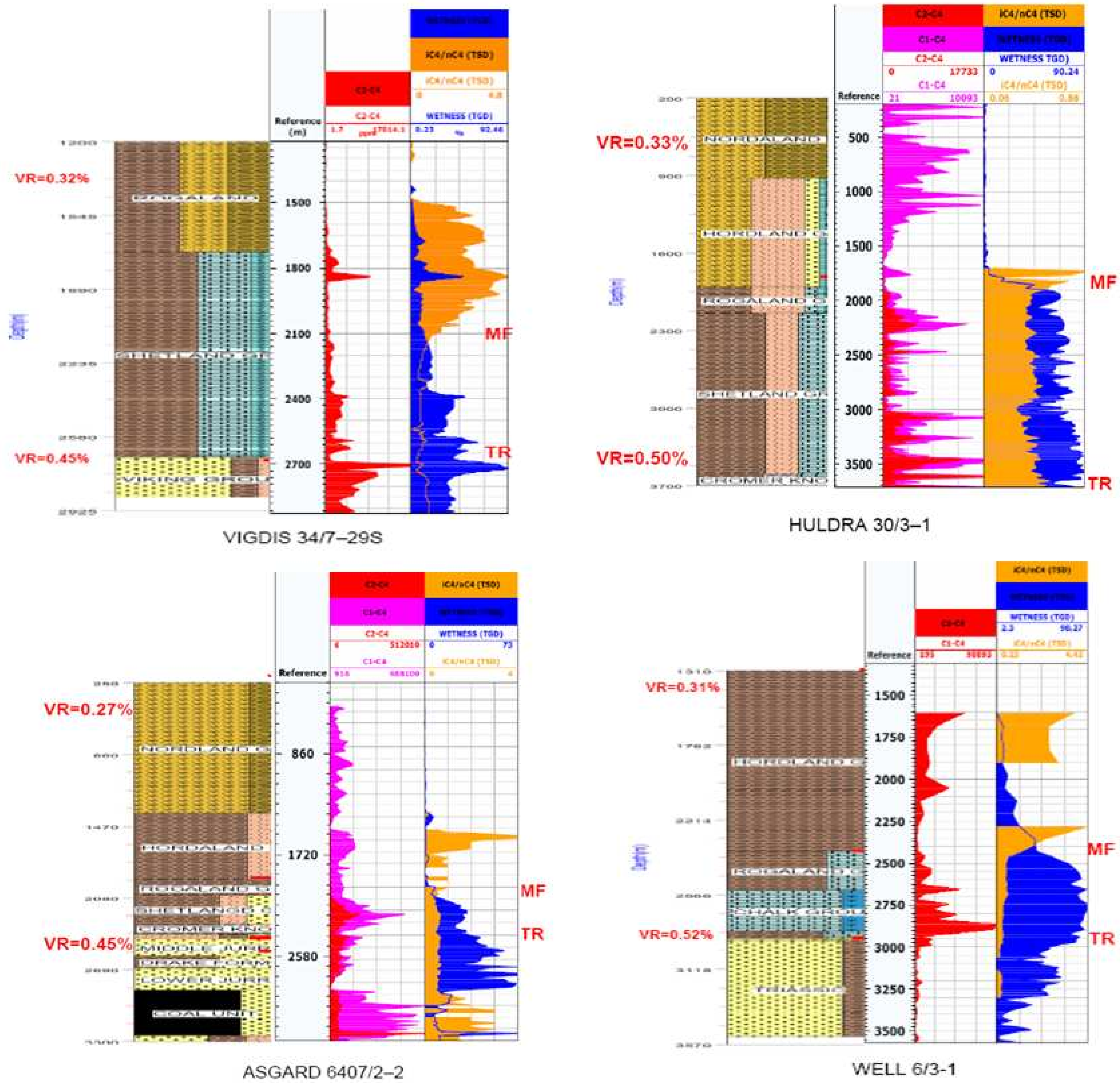

Figure 2. The TGD and TSD profiles of some North Sea Wells

The profiles for the thermogenic wet gas showed a general trend for which thermogenic wet gas content increases towards the reservoir depth wise, while the thermogenic signature decreases towards the reservoir. In some cases i.e. Fram 35/11 – 4 and Gullfaks 7219/8 – 1S (Figure 3) the profiles were not consistently smooth; the observed spikiness may indicate heterogeneity of the formations, corresponding to occurrence of tight zones in the formations (low permeability) which provides for the migrating petroleum to build up the correspondingly required column to overcome the resistance posed by the pores, enabling migration into the tight zones. Hence the profile in a broad scheme represents the variableness of thermogenic wet gas across the formations into the reservoir. The thermogenic wet gas occurred up to 25% in most profiles. The total hydrocarbon content expressed as ppm (parts per million) were up to 80,000ppm for most Norwegian wells. The profiles for some of the wells are presented in figures 2 and 3, showing the trend for the thermogenic wet gas and that for the thermogenic signature (iC_4/nC_4). The distance from the migratory petroleum front as detected by the thermogenic wet gas and signature (iC_4/nC_4) to the reservoir – caprock interface represents the height of the thermogenic wet gas above the caprock and is measured relative to the depth of the reservoir.

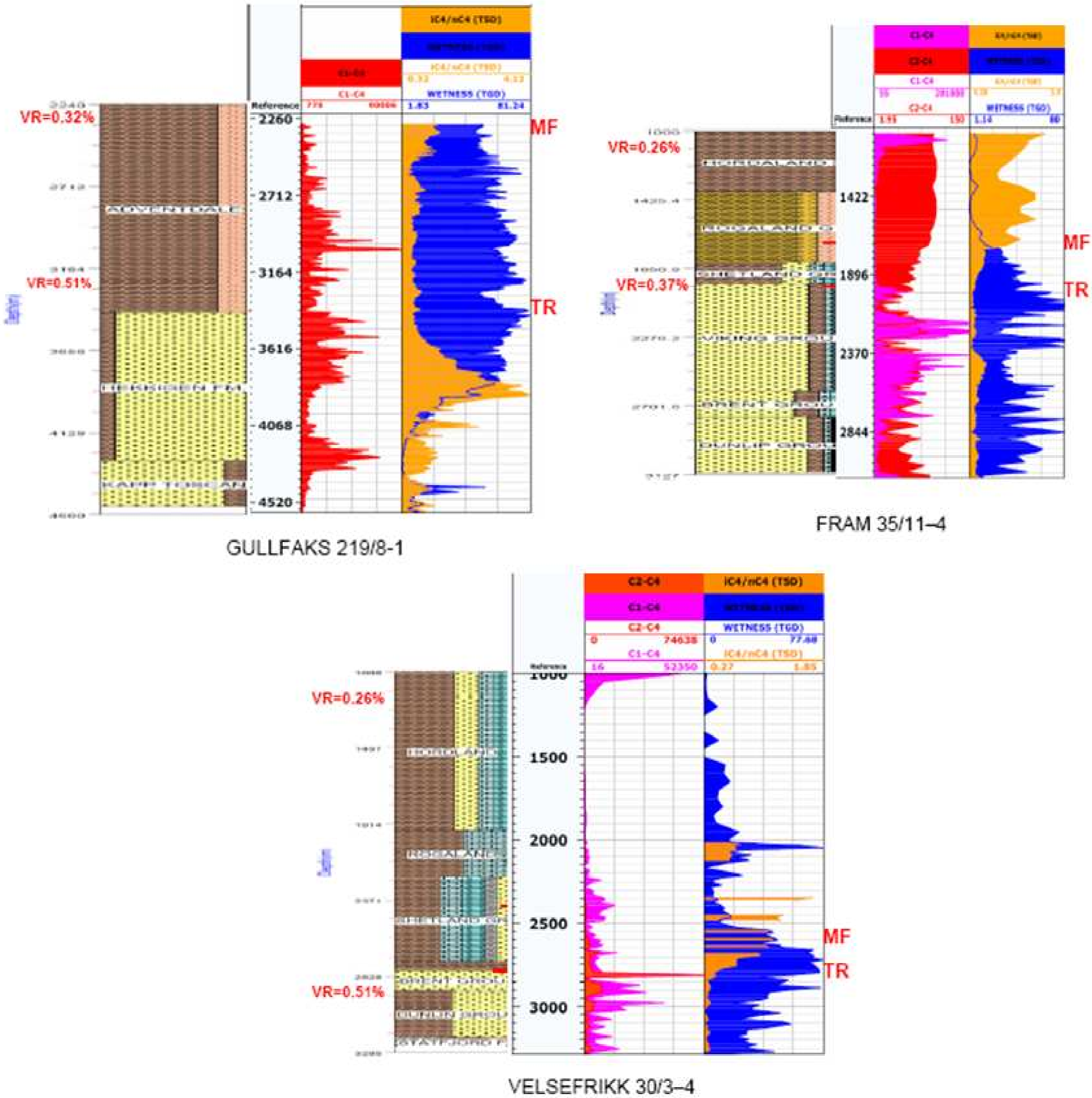

Figure 3. The TGD and TSD profiles of some North Sea Wells

In this study, the height of thermogenic wet gas varies from about 30m which could be termed short distance migration to above 1000m, with thermogenic wet gas content significantly above 20% – 30% of the total hydrocarbon content and the corresponding thermogenic signature less than 1.0. The summary statistics of a larger study involving 50 wells across 41 oil fields indicates in figure 4 that 38% of the wells have thermogenic wet gas heights ≥ 1000m above the reservoir caprocks, 20% has thermogenic wet gas height ≥ 500m while 32% has thermogenic wet gas heights ≤ 500m above the reservoir caprocks. This result implies pervasive (anomalous) occurrence of thermogenic wet gas in the reservoir caprocks and overlying formations in the North Sea.

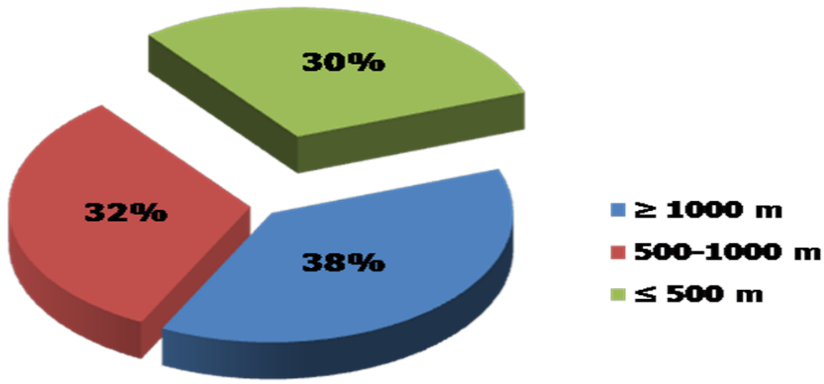

Figure 4. Percent distribution of thermogenic wet gas height.

DISCUSSION

Grouping thermogenic wet gas profiles

A close look at the thermogenic wet gas profiles evokes that the profiles can be grouped based on the hydrocarbon distribution pattern. The profiles show that all the wells bear thermogenic hydrocarbon through to the reservoir – caprock interface, inferring a potential association with down–dip oil leg and could be sourced from a mature source rock or secondarily by thermal cracking from the associated oil in the reservoir. Some profiles show wetter caprock than the reservoir, while some show wetter reservoir than the caprock. The term wetter describes a higher percentage of thermogenic wet gas in the reference i.e. caprock or reservoir. The interval of wet gas is the distance between the reservoir – caprock interface and the migration front. Examples of wells with wetter caprocks are Velsefrikk 30/3–4, Gullfaks 7219/8–1 and Well 6/3–1 while wells with wetter reservoirs are Fram 35/11–4, and Vigdis 34/7–29S. The fact that the caprocks in the profile of the wells mentioned above are wetter may suggest the presence of low capillary pressure caprock at the contact interface overlying the caprock sections with thermogenic wet gas content. This infers a high permeability contact interface with the reservoir underlying the caprock section with high wet gas content, while wells with wetter reservoir may have low permeability or high capillary pressure contact interface (Abrams, 1996; Leith *et al.*, 1993). The interval of high wet gas may be overlaid by a less permeable formation having low migration rate, this may result in the buildup of the necessary capillary pressure allowing the accumulation of gaseous hydrocarbon, which may result in wetter caprock than the reservoir.

The wells with wetter reservoirs i.e. Fram 35/11–4, show that thermogenic wet gas decreases in relative amounts to the total gas with decreasing burial depth. This trend may suggest diffusive leakage along a concentration gradient (Leythaeuser *et al.*, 1983). Where the permeability of the caprock overlying the reservoir is low there may be a temporary setback for migration into the caprock, which results in the accumulation of wet gas with continuous charging of the reservoir to attain the necessary capillary entry pressure for migration of wet gas into the caprock (Abrams, 1996).

Hydrocarbon emplacement mechanism

The hydrocarbon distribution pattern as could be observed from the thermogenic wet gas profiles (figures 2 & 3) show that some wells have continuously high wet gas content in the caprock for up to a Km of the caprock sections. This trend of profile is observed for Huldra 30/3–1 which also has high pore pressure up to 80% of the lithostatic pressure, a handful of the wells (not mentioned in this study) having this characteristic are known to have attained their fracture pressure. Loseth *et al*. (2002) observed that high pore pressure wells usually have high wet gas readings, especially for wells in gas chimneys. This observation invariably indicates that high pore pressure wells with a high potential for fracture of the caprock will most likely have continuously high wet gas content in their caprock suggesting that hydrocarbon could have been delivered into the caprock section due to fracture failure.

The TGD and TSD profiles of some wells with low reservoir pressures and none mature caprock sections also show continuous high wet gas sections, this means that the pressure exerted by the buoyant hydrocarbon column may not have played a significant role in the emplacement of hydrocarbons into the caprock, but leakage may be largely due to the presence of a high permeability contact interface between the reservoirs and the caprocks suggesting that hydrocarbons were delivered into the caprock sections by capillary leakage via network of pores in the caprock matrix via argillaceous lithology. The retention capacities of most of these wells are about 6.8MPa and below inferring that the wells are leaky (Gaarenstroom *et al*., 1993; Nordgard Bolas & Hemanrud, 2002).

CONCLUSION

1. The study indicate that most wells in the North Sea have thermogenic wet gas in immature caprocks overlying reservoirs, which infer caprock leakage.
2. The hydrocarbon emplacement mechanisms indicate that hydrocarbons were delivered into the caprock
(a) via fracture failure due to high reservoir pressure and
(b) capillary failure due to high permeability contact interface via network of pores in the matrix of the caprock.

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