GEOLOGICAL EVALUATION OF AREAS OF THE MISSISSIPPI SUBMARINE CANYON: IMPLICATIONS FOR HYDROCARBON EXPLORATION RISK, THE GOLDEN ZONE CONCEPT AND CONSIDERATION OF THE SIGNIFICANCE OF THE GEOLOGICAL ENVIRONMENT ON MACONDO-TYPE INCIDENTS

EXECUTIVE SUMMARY

In the aftermath of the Deepwater Horizon drilling disaster occurring on well (henceforth referred to as Macondo 252 #1), it is highly pertinent to examine all relevant aspects of engineering and geological risk and uncertainty to help minimise the possibility of recurrent similar disasters. This report examines geological characteristics that can be used to mitigate technical risk during exploration drilling. It studies the geology of the Mississippi Submarine Canyon where Macondo 252 #1 is located and questions the geological uniqueness of that location. The Golden Zone (GZ) concept is evaluated in the context of improving the understanding of overpressure development during drilling.

A huge amount of public domain data is available relevant to the geological conditions in the Mississippi Submarine Canyon. Successful oil-industry drilling is commonplace on the adjacent northern continental margin of the Gulf of Mexico (GoM). The modern seafloor in the canyon is a dynamic environment with a 17,000 year history of gravitational slumping, shallow seismicity, oil and gas seeps and outcrops of gas hydrates. A link exists between slumping and subsurface overpressures.

Temperature (T) is identified as the critical control on the stability of minerals in mudstones and sandstones during their progressive burial. Once the burial temperature exceeds 60°C, mechanical compaction, which dominates the rate of porosity loss until that point, becomes insignificant. Mineralogical changes in mudstones occur rapidly at temperatures above 60°C and cause rapid decreases of porosity and permeability. In sandstones the rate of porosity loss is rapid above 120°C, when the rate of quartz cementation increases exponentially. Both these processes make strata susceptible to high overpressure that in turn may lead to the development of hydraulic fractures. The GZ concept embraces the significance of the 60°C and 120°C isotherms on porosity, permeability and pore pressure, and identifies that more than 90% of the Earth's light oil and gas occur in the same thermal window. This provides a scientifically robust foundation for understanding processes relevant to mitigating risk hydrocarbon exploration. The severe problems experienced while drilling Macondo 252 #1 occurred at slightly less than 120°C, at the base of GZ.

In the context of the GZ concept, the well-control problems, experienced in Macondo 252 #1 (e.g. mud losses and blow out) typify drilling into hydraulically-fractured strata. The formation was loose rock material suspended in overpressured fluid with extremely little physical integrity. An overestimation of the rock strength in the blow-out interval may have been caused by a failure to recognise the significance of anomalously low leak-off tests from wells in the Mississippi Canyon. When drilled with a high mud-weight, disintegration of the

formation and loss of drilling mud would occur. However, when mud weight is reduced, conditions that lead to a blow out will ensue. The physical integrity and confining stress of the formation is so low that cement introduced to stabilise the formation would fail, as there is so little to bond to and as cement is lost into fractures.

Hydraulic fracturing of strata in the GZ may be triggered by unloading of overlying sediment during large-scale slumping on the seafloor of the modern Mississippi Canyon. High flow-rates of warm, natural oil from fractures on the seafloor indicate that leakage is occurring from GZ depths at the present day. This model assumes that unloading causes an instantaneous convergence of the hydrostatic and lithostatic gradient that promotes the hydraulic fracture of already overpressured strata. The hydraulic fractures will initiate leakage of oil to the seafloor and weaken the strata that will remain susceptible to further physical disruption and possible disintegration when drilled.

As temperature controls porosity and permeability loss, at depths greater than 60°C isotherm, models that use mechanical compaction as their basis will inevitably fail to make consistent and reliable pre-drill predictions of overpressure. In the face of the importance of temperature control on pressure, and the large public-domain database from the offshore GoM, it is remarkable that the GZ concept or similar concepts are not routinely used to support safe and optimal drilling practice.

Definitions of High Pressure High Temperature (HPHT) conditions that use material stabilities at absolute temperatures and pressures are inappropriate for defining geological HPHT conditions that are encountered during drilling and where and when overpressure occurs. Use of HPHT definitions for material stabilities, for example T = 149°C as the onset of HT, to describe geological HPHT environments is clearly misleading as geological HT occurs at 120°C. The temperature difference (29°C) equates to 1-1.5 km difference in depth (dependent on geothermal gradient) for the onset of HPHT conditions. Geologically-young formations (Miocene (~ <23 Ma and younger) are particularly susceptible to low rock strength and overpressure in the temperature window between 120-149°C and thus have a substantial risk of being ignored as sensitive formations if the pre-drill lower boundary for HPHT is 149°C.

To improve the geological predictability of the presence of formations in the GoM that are susceptible to producing Macondo 252 #1-type disasters, several simple steps can be taken: 1) mapping of the GZ, 2) incorporating temperature relationships in pore-pressure modelling, 3) mapping of low-confining stress and weak formations using LOP data from adjacent wells, 4) evaluating and mapping seafloor hydrocarbon seeps, 5) mapping the distribution of slump scars, and 6) evaluating the origin and significance of local seismic events. More generally, the definition of HPHT conditions will benefit from including a far better account of the geological characteristics that control HPHT environments.

From a geological perspective it is very unlikely that the drilling problems in Macondo 252 #1 are unique. Other wells located in the Mississippi Canyon's slump scars would behave similarly. Submarine slumps and slides are common features of many hydrocarbon provinces and conditions similar to those encountered in Macondo 252 #1 and more generally in the vicinity of the Mississippi Submarine Canyon are expected to occur. The GZ concept has global relevance and allows lessons learned from different locations to be shared within a unifying geological concept. This will be of direct benefit to industry partners and secure safer as well as more effective drilling practice.

Drilling the Macondo 252 #1 well was rich in geological challenges and certainly not just an engineering nightmare. Drilling into the Golden Zone at this depth, temperature and location should have been predictably challenging and required appropriate and thorough pre-drill modeling of pore pressure evolution, and great caution. Anything less inevitably would contribute significantly to the blowout disaster as seen on April 20, 2010.

CONTENT

INTRODUCTION

The Deepwater Horizon Disaster occurred while completing drilling operations on the Macondo 252 #1 well, located in the Mississippi Canyon in an area of major slump scars on the submarine slope adjacent to the Mississippi delta (Figure 1). Here the ocean floor is a dynamic environment with ongoing gravitational slumping that is associated with seismicity, active high-rate natural oil and gas seepage from fractures on the ocean floor, and gas hydrates commonly occurring. Natural seepage of hydrocarbons is a clear indication of an active subsurface petroleum system, and is known to have occurred at least as long ago as the early visits of European explorers to offshore Louisiana. In the context of Macondo 252 #1, it is relevant to understand whether the geological conditions in this area of the Mississippi Canyon are unique in terms of their potential affect on hydrocarbon borehole drilling (**PWRPT2**[1]), and thus unlikely to be foreseen or predicted, are symptomatic geological conditions, and hence possibly relevant to other geologically similar areas, or are commonplace circumstances that would make geological understanding of only marginal relevance to design of a drilling program.

In this report, I examine the geological conditions and evaluate their relevance to appropriate exploration procedures in the Mississippi Canyon area (PWRPT3) and elsewhere. I investigate the relevance of the Golden Zone (GZ) concept developed and applied by Statoil (Buller et al. 2005; Nadeau 2011a) to hydrocarbon exploration and pore-pressure prediction. The GZ concept is based on a huge publically-available global data base and underpinned by two decades of fundamental research that investigates the temperature-driven reactions that modify the mineralogy, porosity and permeability of sediment as it transforms into sedimentary rock during burial. The GZ concept may provide a unifying empirical theory for understanding where hydrocarbons occur in commercial volumes (Buller et al. 2005), but also has direct relevance to understanding the occurrence of overpressure and natural fracturing of formations, and thus has implications for improving drilling practice (Nadeau 2011b). If the claims made in publications by Statoil are correct, the GZ concept allows accurate and internally-consistent prediction of overpressure in the Gulf of Mexico (GoM) (Ehrenberg et al. 2008a; Nadeau 2011a,b).

Drilling of the Macondo 252 #1 well and the consequent loss of life, environmental damage and economic impact on the operators of the well and inhabitants of the immediate hinterland has triggered an urgent re evaluation of geological risk. There is an industrial obligation, as well as a social responsibility, to learn and ensure that similar mistakes are avoided in the future. It is recognised that many subsurface-engineering solutions require the transfer of appropriate and accurate geological data in order to facilitate optimal engineering design. One cannot realistically hope for problem-free engineering design if significant geological information is ignored. Here, I examine some fundamental aspects of the geology of sedimentary basins with specific focus on those that are, or have the potential to be, hydrocarbon bearing. The overall aim is to provide insight into what geological information/data were available, and/or should have been sought, when exploring for

[1] **PWRPT** references are to slides in the accompanying powerpoint presentation. Please note that not all powerpoint figures are referenced and that they appear in a different order in the written report than in the powerpoint presentation. The numerical suffix indicates the slide number in the powerpoint presentation.

hydrocarbons on potentially unstable submarine slopes[2]. I consider how these should have been used to constrain and minimise safety and environmental risk while optimising economic gain. Macondo 252 #1 has given us an opportunity to learn from mistakes, a fundamental element of how to progress science and technology. There is an industry obligation and well as a social responsibility to learn and ensure that similar mistakes are avoided in the future.

There are many technical risks associated with drilling hydrocarbon-exploration wells. Fundamental in the process of exploration is the identification of the sites of prospective areas (plays) and individual prospective targets (prospects), and assessing whether the cost of drilling an exploration well is likely to yield an economic return (as saleable hydrocarbon volumes), the probability of that happening, and at what geological risk. Geological hypotheses are generated, and assuming that economic and strategic goals are met, wells are drilled to test these hypotheses. Because exploration wells have uncertain outcomes, in the sense that their results may not match pre-drill prognoses, it is vital that geologists communicate their uncertainties to engineering colleagues who design and execute drilling. Operating the Macondo well was successful in confirming the geological hypothesis that oil was present in highly productive reservoirs, but clearly was unsuccessful in achieving that goal in an acceptable operational manner. Associated with the presence of hydrocarbons is the inherent risk of encountering elevated pore pressure, typically termed overpressure,[3] during drilling; hydrocarbons are not the sole cause of overpressure.

THERMAL STRUCTURE OF SEDIMENTARY BASINS

The sedimentary rocks that form hydrocarbon systems started life as sediment in which locally high concentrations of organic matter (often algal) in some muds later formed source rocks that generated hydrocarbons. These occurred on ocean or lake floors or elsewhere on the earth's surface. Successive periods of sedimentation progressively bury the sediment that in response to the increasing mass of overlying material (the overburden) compacts by mechanical rearrangement of grains (and some minor breakage and compaction of brittle and soft grains, respectively). Thereby, the porosity and fluid content are reduced. Burial rates of sediment vary hugely and the Mississippi Canyon has among the highest rates known, up to ~10,000 m/million years; in comparison the North Sea burial rates are generally 10 to 100 m/million years (Nadeau 2011a). The cumulative load of accumulating sediment is termed the lithostatic gradient, which approximates to a curvo-linear relationship between burial depth and pressure (Figure 2). When the burial of sediment commences,

[2] Submarine slopes are areas of the ocean floor seaward of continental margins and the deep-ocean floor; they are generally inclined at <4 degrees.

[3] Overpressure exists when the pressure of fluids in the pores exceeds the hydrostatic pressure (equivalent to the mass of overlying column of water). When overpressure occurs, the fluid content of rocks supports the overlying mass of sedimentary materials (the overburden), which typically is supported by the granular fabric of strata.

porewater[4] fills all the non-solid parts of the sediment, i.e., the pores. As sediment compacts, the interstitial porewater is expelled and seeps upward toward the Earth's surface[5].

Sedimentary basins are characterised by large-scale and continuous expulsion of porewater and other fluids throughout their burial history. The porewater creates a load which increases linearly with depth of burial (= height of the water column) termed the hydrostatic gradient (Figure 2). The hydrostatic pressure gradient is less steep than the lithostatic gradient, and consequently, an increasingly greater load is carried by the granular framework as sediment burial increases. Concomitant with increasing the overburden load, the ambient temperature of the rock and fluid gradually increases. This progressive increase in temperature is approximately linear and is termed the geothermal gradient; in sedimentary basins, the geothermal gradient is typically between 20 and 40 °C per kilometre of burial[6].

Most mineral and organic components of siliciclastic[7] sediment are unreactive in the aqueous fluids in which they are deposited and buried until they reach approximately 60°C (~140°F)[8]. Consequently, up to approximately 60°C sediment loses its porosity and expels porewater by mechanical compaction of grains. Above 60°C, a series of thermally-controlled mineral transformations occur that change not only the mineralogy but also the porosity, pore-size distribution, bulk density, permeability and rock-physical properties (e.g. tensile strength, ductility). Study of thermally-controlled reactions in mudstones and their potential influence on hydrocarbon habitat and migration has a long history (Weaver 1960; Burst 1969; Hower et al. 1976). Clay mineral stability ranges have been used extensively for estimating the maximum temperature to which mudstones and sandstones have been exposed (Figure 3). Since this early work, the investigation of the thermal transformations of clay minerals has advanced considerably, and became the basis for development of the fundamental particle theory (Nadeau 1999) that helped elucidate the physical character and behaviour of clay minerals as they were exposed to successively higher burial temperatures. The fundamental particle theory is a critical element in improving the understanding of the behaviour of pore-pressure evolution during burial as it demonstrates that clay mineral transformations take place by mineral dissolution and precipitation and not by solid-state transformation.

In the US Gulf Coast, the predominant clay mineral reaction is the transformation of smectite to illite (Hower et al. (1976). This reaction typically begins at 60°C[9] and marks the shallow or low-temperature limit at which temperature-driven reactions take over as the main modifiers of the physical properties of rocks during burial. Other clay minerals destabilize at

[4] Seawater in marine sediment, freshwater in terrestrial sediment – this water is termed porewater (interstitial fluid) as it fills pores. Pores are the voids between the granular constituents of sediment and constitute the porosity of the sediment.

[5] Earth's surface can be the seafloor or a terrestrial surface.

[6] Variations within this range occur both locally within sedimentary basins and regionally between sedimentary basins.

[7] Siliciclastic minerals are quartz and silicate minerals that are the main constituents of sand, sandstone, mud and mudstone.

[8] There are exceptions to this, such as naturally-occurring calcium carbonate and silica, which form the shells of marine creatures. When the creatures die, the minerals, aragonite and opal A respectively, transform into more stable minerals with the same chemical composition; aragonite transforms to calcite and opal A transform to opal C, opal CT and finally quartz. Neither mineral forms a major component of sand stones, although opal can very common in muds and mudstones.

[9] Thermal destabilization of smectite may be delayed until ~80°C (~176°F) if carbonate minerals are present.

progressively higher temperatures, and new clay minerals, in particular illite, form. All the mineral transformations contribute to a decrease in permeability by several orders of magnitude (Nadeau et al. 2002a,b; Schneider et al. 2003). This dramatic change in permeability decreases the ability of porewater to escape, or permeate through mudstones, thus making them more susceptible to developing overpressure.

A second thermally-constrained mineral reaction occurs at >120°C (~248°F), when quartz cementation in sandstone develops rapidly. This observation was made following extensive and detailed evaluations of sandstone reservoirs in the North Sea that were made to improve the prediction of reservoir quality at depth (Walderhaug 1994, 1996; Aase et al. 1996; Bjørkum et al., 1998; Oelkers et al., 1996, 1998, 2000; Walderhaug et al. 2000, 2004). It became apparent that the reservoir-quality prediction work had implications for overpressure development, seal failure, hydrocarbon migration, and overall exploration risk assessment. This had specific relevance to understanding why numerous exploration wells at depths of ~4km and temperatures >120°C had only residual hydrocarbon columns from formerly large oil and gas accumulations in good-quality reservoirs whose seals had failed hydraulically due to fluid overpressure exceeding the fracture gradient[10]. It became apparent that the exponential increase in the rate of porosity loss caused by quartz cementation was a major contributor to overpressure development and failure of low permeability mudstone seals.

Above 120°C, the rate of quartz cementation in sandstones begins to increase exponentially as a function of temperature. Above 120°C, porosity loss is unaffected by overpressure or reductions in effective stress (Bjørkum 1996), the latter is expected during mechanical compaction. As cells of overpressure develop, their areal extent becomes dependent only on the pressure at which hydraulic fracture occurs and the location of lateral drainage or leak-off points that can facilitate pressure loss. Consequently, overpressure will rise until hydraulic seal failure occurs at which time all aqueous and hydrocarbon fluids below the seal escape vertically through hydraulic fractures (Hubbert and Willis, 1957; Lothe et al., 2005). The migration of these fluids into shallower parts of sedimentary basins is very significant with respect to the prediction of drilling risk in shallower intervals (Nadeau, 2011b).

Summary Refined understanding of the physical behaviour of clay minerals in response to increased temperature above 60°C has elucidated how some clay minerals dissolve while others grow, and in doing so, irreversibly lower the permeability of mudstones. Lowering the permeability makes expulsion of porewater more difficult and makes the mudstones more susceptible to becoming overpressured. Above 120°C, the rate of quartz cementation increases rapidly, and porewater is expelled from sandstones and acts as a further source of overpressure. If unable to dissipate, overpressure rises until it exceeds the pressure required to fracture seal lithologies, at which time hydraulic fracturing occurs. All the mineral reactions and consequent reductions in porosity and permeability are thermally driven.

[10] Macondo 252 #1 crude oil has a measured reservoir temperature of 117°C (243°F), in the hot end of the Golden Zone. Exhibit 7239; Deposition of Haug (Morten) Emilsen, p. 84, line 6 – p. 88, line 17; BP Gulf of Mexico SPU Technical Memorandum: Post-Well Subsurface Description of Macondo well (MC 252)", p. 34 – BP-HZN-BLY00140906. Most likely reservoir temperature is quoted as 113°C (235°F) in BP Gulf of Mexico SPU Technical Memorandum, 26th May, 2010.

Golden Zone

The thermal structure outlined in the previous section provides the basis for the Golden Zone (GZ) concept, which recognizes that most (>90%) of the Earth's light oil and hydrocarbon gas reserves occur in a thermal window between 60 and 120°C (Figure 4; **PWRPT11**). In sedimentary strata cooler than 60°C, there is a rapid decline in abundance of reserves (Figure 5; **PWRPT12**). Above 120°C, there is an exponential decline in abundance of reserves. Buller at al. (2005) claim that the GZ concept is "an empirically verifiable theory showing that hydrocarbons in siliciclastic sedimentary basins of the world generally occur in a predictable manner controlled by temperature" and, that "the impact of this theory on exploration practice is potentially profound." Buller et al. (2005) refer only to siliciclastic reservoirs but Statoil have since expanded the data base to include carbonate reservoirs (Ehrenberg and Nadeau 2005; Ehrenberg et al. 2007; Ehrenberg et al. 2008b).

An attractive feature of the GZ concept is that it is based on a huge (>120,000 reservoirs[11]) data base of public-domain data, which includes the GoM offshore reservoir data base, the largest and most comprehensive of its kind in the world (Ehrenberg et al. 2008a). Any organisation or individual can access and use the same data if so minded, thus enabling creation of GZ or similar concepts that seek foremost to provide an objective view of "what is known" about local and global hydrocarbon distribution. I am unaware of any similar concept in the public domain or the level to which the GZ concept is accepted and adopted in the oil industry[12].

Defining the "Earth's energy" GZ (Nadeau 2011a) was a consequence of two independent avenues of mineralogical research: 1) the fundamental particle theory of clay mineralogy (Nadeau et al., 1984; Nadeau 1999), and 2) the surface area precipitation-rate-controlled models for the formation of diagenetic (quartz) cements[13] in reservoirs (Walderhaug 1994, 1996; Aase et al. 1996; Walderhaug et al. 2000). Both avenues of investigation concluded that the mineral reactions observed are thermally driven and largely unaffected by pressure. In combination, these form "the empirically verifiable theory" of Buller et al. (2005). The commercial impact (to Statoil) of the GZ concept is undocumented, but the utility of using a thermally-based concept for screening analyses of exploration areas is obvious, as if correct, it provides a basis for prioritising exploration (>90% probability) to lie within a restricted thermal window globally[14]. Examples of applications supported by the GZ data include the North Sea, Bombay Basin and GoM (Nadeau et al. 2005; Bjørkum and Nadeau 2008; Ehrenberg et al. 2008a), and a specific example of an application of the data is to show how many exploration wells are drilled to temperature (T) >120°C but rarely make commercial discoveries.

Even without considering the relevance of thermally-driven mineralogical reactions to pore-pressure development, the relationship between temperature and pore pressure is visually obvious when pressure-profiles are plotted against temperature. A single sharp increase in pore pressure above the hydrostatic gradient (overpressure ramp) typifies basins globally

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[11] 120,000 data are mainly from producing reservoirs (Buller et al. 2005).

[12] MSc students on the University of Aberdeen MSc in Integrated Petroleum Geoscience have been taught about the Golden Zone for at least a decade.

[13] Diagenetic cements are the minerals that form during the burial of sediment and convert them gradually into sedimentary rock.

[14] Within these areas, traps of commercial size need to be identified independently.

(Figure 6; **PWRPT14**); these relationships have appeared in many Statoil publications for several petroleum basins worldwide. When depth[15] is plotted against porewater pressure for a series of basins, the overpressure ramp varies from basin to basin. This implies that overburden load does not have significant influence on the development of overpressure, whereas temperature obviously does. Plots such as Figure 6 verify the "empirical ..... GZ theory." The relationship between overpressure and temperature demonstrates that the development of overpressure can begin as early as 60°C and may reach near lithostatic conditions by 120°C. Thus, one can conclude that specific lithostatic loads are not required to generate overpressure[16].

As a consequence of the simple relationship between temperature and pore pressure, it is no surprise that a similar onset of overpressure exists globally, independent of location, basin style, geological age, sedimentation rate, subsidence rate, geothermal gradient, hydrocarbon volumes or even sizes of hydrocarbon accumulations. If the geothermal gradient is known, the GZ concept should in theory be able to predict the depth interval where most hydrocarbons will occur and where overpressures are most likely. Other important aspects of the thermal structure of the earth's crust have been extensively studied, in particular the thermal stability and evolution of the kerogen from which hydrocarbons are derived, that combined with the GZ allow a three-fold thermal zonation to be defined that captures the characteristics of active hydrocarbon systems (Figure 7; **PWRPT13**).

The 200°C and 120°C isotherms bound the *expulsion zone*, which is where hydrocarbons are generated, porosity and permeability are low, and pore pressure can cause the hydraulic fracture of strata. Most hydrocarbons are expelled upward from this zone, hence the *expulsion zone*. As noted in footnote 3, the Macondo 252 #1 reservoir temperature is 117°C, which is very close to the boundary of the *expulsion zone* and *accumulation zone*. A reasonable inference from the GZ data (Figures 5 and 7) is that at the reservoir temperature encountered in the Macondo 252 #1 well, one would expect the onset of HPHT conditions that may be accompanied by overpressure and possible development of hydraulic fracturing.

Above the expulsion zone is the *accumulation zone* into which hydrocarbons migrate through hydraulic fractures. The *accumulation zone*, equivalent to the Golden Zone, is where the majority of commercially extracted hydrocarbons are trapped. In the *accumulation zone* hydrocarbon-charged reservoir sandstones act as combined pressure-relief and separation tanks, sealed by low permeability seal (mudstones/shales) that greatly decrease the rate at which hydrocarbons can seep but allow formation water to pass through them. Sandstone porosities and permeabilities in this zone are still quite high because the volume of quartz cement is normally too low to fill the pores. The upper limit of the *accumulation zone* is the 60°C isotherm.

The accumulation zone is a zone of transition between the thermo-chemical compaction regime of the expulsion zone and an overlying interval where mechanical compaction dominates – the *compaction zone* (Nadeau 2011a). In the *compaction zone*, at temperatures <60°C, hydrocarbon volumes are low because the influence of vertical, fracture-controlled re-migration is minor. Those hydrocarbons that are present, apart from local biogenic gas, have probably migrated upward from the underlying accumulation zone through laterally-

[15] Depth representing the lithostatic load of sediment.
[16] This will be considered again later in the context of the definition of HPHT conditions.

extensive sandstone or siltstone 'carrier' beds. It also is widely known that oil in this zone is vulnerable to bacterial degradation (*biodegradation*). This is a common phenomenon in oil reservoirs where temperatures are less than 80°C (Head et al. 2003).

A fourth zone where T >200°C is termed the *depleted zone* from which no significant hydrocarbons are generated and porosity and permeability of reservoirs are extremely low.

A regional example of the Golden Zone distribution from the GoM shows that the 60°C and 120°C isotherms cut strata of all ages and deepen southward (offshore) where geothermal gradients are lower. The top of the HPHT zone (the 120°C isotherm) is independent of depth or geological age (Figure 8).

In the mid/late 1990's, Schlumberger provided an informal, independent confirmation of the GZ concept when Statoil's planned development of Smørbukk field (offshore mid-Norway, reservoir temperature, T = 165°C) required production logging tools. Schlumberger did not have logging tools designed to operate at that temperature because there was no commercial market. Schlumberger explained that 95% of oil and gas reservoirs occurred at T <126°C. Interestingly, at the same juncture Schlumberger was able to confirm that their exploration logging tools could handle T up to 200°C. This provision of technology confirms the practical relevance of the GZ and an oil industry persistence to explore for less likely reward at higher temperatures as documented by Nadeau et al. (2005).

Against the Golden Zone

The three-fold zonation (Figure 4; **PWRPT11**) is quite possibly an implicitly recognized concept in the hydrocarbon exploration community, but there is no direct confirmation of this. Citation indices indicate that the fundamental research papers that underpin the GZ concept are high (often >100 citations), whereas the papers dealing directly with the GZ concept have much lower citations (<30 citations)[17]. The citation indices do not give any indication of whether the Exploration and Production (E&P) industry is aware of or is applying GZ concepts.

Two conflicting geological arguments that counter the GZ concept are identified:

1) generation of secondary porosity during increased burial[18];

2) the presence of oil arrests the cementation (porosity loss) in reservoirs.

If substantially correct, both these factors will produce many occurrences of anomalously high porosity with increased burial (implicitly implying higher temperature).

A body of work appeared from the late 1970's (e.g. Schmidt and Macdonald 1979; Surdam et al. 1984) that claimed that the porosity of sandstone reservoirs was increased during burial by late-stage (deep burial) generation of secondary porosity. Interpretation by the

[17] The lack of citations is likely to be influenced by the fact that the GZ concept papers are more recent, hence have had less opportunity to be cited.

[18] Secondary porosity develops when the primary granular components of sands dissolve or partially dissolve during burial thereby creating pores that previously did not exist. While there is overwhelming evidence that some mineral grains dissolve during burial, there is no evidence that in general mineral dissolution actually increases the total porosity. It is assumed that the progressive thermally-driven cementation of pores commences at T > 60°C once the influence of mechanical compaction is minimal.

proponents of secondary porosity used mineral-textural features from petrographic data[19] that were readily open to at least equally-reasonable alternative interpretations. More importantly, the chemical reactions required to form extensive secondary porosity required unfeasibly large fluxes of porewater, which made the process untenable (Bjørlykke 1984; Giles et al. 1992). Despite evidence to the contrary, supporters of the significance of secondary porosity in reservoirs remain to the present day, even though substantial quantitative evidence and reasonable scientific argument refutes the mechanism (Bjørlykke 1984; Giles et al. 1992; Bjørkum and Nadeau 1998). As the GZ data base shows, sandstone (and limestone) porosity decreases with increased burial and heating (Ehrenberg and Nadeau 2005; Ehrenberg et al. 2008a,b; Esrafili-Dizaji and Rahimpour-Bonab 2009)[20].

Arresting reservoir cementation in oil-saturated sandstones is a mechanism that contradicts GZ concepts, and was used to explain why high porosity was preserved in some deeply-buried reservoirs (Gluyas and Coleman 1992; Gluyas et al. 1993; Marchand et al. 2000). Detailed petrography that included granular-surface-area measurements and study of the kinetics of quartz cementation completely refutes the oil-porosity-preservation model and established the basis of quartz cementation as a precipitation-rate-controlled reaction (Walderhaug 1994, 1996; Aase et al. 1996; Bjørkum et al. 1998; Oelkers et al. 1996, 1998, 2000; Walderhaug et al. 2000, 2004) and reviewed by Nadeau (2011a). When T >120°C, the rate of quartz cementation in sandstone increases exponentially as temperature increases (Walderhaug et al. 2001). Oil does not arrest porosity loss as long as the reservoir remains predominantly water-wet and the S_{wir} ≥10%[21].

A more minor issue concerns the characteristics of the *compaction zone* in which Buller et al. (2005), who refer to this as the *sealing zone*, state that “at temperatures <60°C, hydrocarbon volumes are low because the influence of vertical, fracture-controlled re-migration is minor.” While agreeing in general that a *compaction zone* exists in which regional seals occur, it is apparent that in many hydrocarbon provinces pervasive fractures exist that compromise seals and act as active migration pathways. An excellent example of this is the in the area of the Mississippi Submarine Canyon where individual present-day oil seeps (through the *compaction zone*) flow at >100 barrels/day (MacDonald et al. 1993). This is strong evidence of a deep-rooted open fracture system along which oil is flowing. I assume that Buller et al. (2005) are considering geological situations in which sudden unloading of strata has not occurred.

Summary The three-fold thermal zonation, within which the Golden Zone (GZ) is synonymous with the *accumulation zone*, is consistent with much prior knowledge of the thermal structure of the shallow crust. However, by integrating an improved understanding of the thermal stability of minerals, specifically between 60°C and 120°C, relationships between mineral dissolution and growth, and the consequent modification of permeability, allow the process of overpressure generation to be clarified. Mudstones and sandstones undergo similar porosity reduction that decreases with increased temperature. The huge reservoir data base used to define the GZ makes alternative models for porosity development and

[19] Petrographic data are derived from laboratory micro-scale examination of rock samples, typically as thin sections.
[20] Note that local preservation of porosity does occur during burial in the GZ, for example, when the clay mineral chlorite coats sand grains (Ehrenberg 1993). Secondary porosity may also develop associated with fluid flow and mineralisation along faults and fractures.
[21] S_{wir} = irreducible water saturation.

preservation unlikely. The GZ concept is an excellent unifying model that is internally consistent and rooted in high-quality science. It has fundamental significance in many predictive aspects of petroleum geology.

ENCOUNTERING OVERPRESSURE DURING DRILLING

Overpressure is a common occurrence in hydrocarbon exploration boreholes and is particularly prevalent in high-pressure high-temperature (HPHT) geological environments (for global summary statistics, see Nadeau 2011b). Despite this, industry practice rarely has major problems with conducting drilling operations in which the overpressure causes significant safety, environmental or economic problems. However, in HPHT operations these problems are more prevalent. In the US GoM, overpressure is encountered commonly throughout the lower part of the Golden Zone with high (>1.7 g/cm^3 SG) pore pressure concentrated in reservoirs with >120°C in the expulsion zone (Figure 9; **PWRPT15**). Interestingly, when the same reservoir data are plotted against mean sedimentation rate there no clear relationship between pore pressure and burial rate (Figure 10). If mechanical compaction was a dominant mechanism to promote elevated pore pressure at >60°C, an obvious relationship with burial rate should be apparent.

Examination of global leak-off pressures[22] (LOP's) shows the significant occurrence of anomalously low LOP's, particularly for offshore Louisiana (Figure 11; **PWRPT20**)[23]. These low LOP's are located in and adjacent to the Mississippi Canyon (Figure 12; **PWRPT5**).

In geological conditions with confined lateral drainage, the probability of reservoir pore pressures exceeding the minimum rock-stress increases exponentially as a function of temperature. Where high minimum rock-stress occurs, this may not pose serious challenges to deepwater drilling operations because the formation integrity is maintained by the high confining stress, as is suggested by the global trend of high LOP tests (Figure 11). Prevailing low minimum rock-stress means that the maximum pore-pressure required to fracture low permeability strata (e.g. mudstone seals) may be anomalously low, possibly at <1.5 g/cm^3 pressure gradients. Severe well-control problems may occur during drilling (Nadeau 2011b) when fractures are encountered in strata with low confining rock-stress and higher-than-expected pore-fluid pressure, such as:

a) lost circulation of fluid (drilling mud loss into the formation),

b) excessive requirements for materials to control lost circulation,

c) major returned flow of fluids to the surface (fluid and gas kicks) when mud weight is reduced in an attempt to reduce lost circulation.

[22] Leak-off pressure (LOP) tests are performed by pumping drilling mud at a constant rate into the borehole to stimulate fracture of the borehole wall. Normally an LOP test is only performed until the mud begins to leak into the formation, i.e. the point at which fracture in the borehole wall initiates. The point at which hydraulic fractures begin to propagate into the adjacent formation is termed the formation break-down pressure (FBP), which is typically ~10% greater than the LOP. Once the FBP is reached, disintegration by hydraulic fracture of the formation occurs so long as the fracture propagation pressure (FPP) is maintained (Figure 7). Note that the LOP and FPP may have similar values.

[23] LOP's with values <1.7 g/cm^3 equivalent mud-weight gradients are of concern for drilling operations (Nadeau 2011b). At depths >3km subsea in offshore Louisiana anomalously low LOP's are common.

If an operator fails to realize that LOP tests are actually FPP's (they are typically close to the minimum stress value and have very similar values to LOP's, Figure 13; **PWRPT18**), there may be an indiscernible drilling-safety margin before reaching formation breakdown pressure (FBP, Figure 13) at which point extensive hydraulic fracture of the near-borehole wall occurs. At FBP fractures propagate away from the borehole and deep into the formation. This causes large-scale loss of drilling mud and possibly complete disintegration of the formation adjacent to the borehole[24]. If the formation loses its physical integrity and disintegrates, well completions, casing and cementation will be extremely difficult to carry out. Consequently, any attempt to create a pressure barrier in the interval damaged by fracturing will be extremely challenging if not impossible. Decreasing mud weight will make the borehole susceptible to blow out.

Clearly huge well-integrity problems may be caused by failing to recognise the significance of anomalously-low minimum rock-stresses during drilling. The problems are at least two-fold: 1) pre-drill evaluation must seek to recognise whether geological conditions exist that cause low minimum rock-stresses; 2) interpretation of LOP's from adjacent or geologically-analogous-boreholes is requisite to understanding and predicting where and how formation breakdown will occur. To achieve this, the subsurface geological conditions that give rise to low minimum rock-stress conditions and elevated fluid pressures have to be mapped and depth to rock-stress relationships need to be defined. With this information, well design and operating procedures can be carried out to manage the anomalous pore-pressures. Finally, criteria for recognising where in the subsurface wells cannot be safely drilled or completed must be established. It is a priority to include LOP's in this analysis.

Predicting pore pressure

Prediction of overpressure is a key feature of quantitative basin modelling and numerous commercial software packages are available to support this task. Waples (1998) states that "the ability to consistently and correctly predict pressures is critically dependent upon including all processes relevant to pressure in the model, and providing accurate values of the critical parameters." In his paper, which reviews basin modelling practice, there is no evidence that Waples recognises the possible significance of thermal processes on pore pressure. In the light of the earlier and contemporary work that underpins the GZ concept (Giles et al. 1992; Walderhaug 1994, 1996; Aase et al. 1996; Bjørkum and Nadeau 1998; Bjørkum et al. 1998; Oelkers et al. 1996, 1998), this is surprising. More disappointing is that Waples does not acknowledge the significance of thermal parameters discussed in Giles et al. (1998), a paper in the same volume from the same conference, that uses extensive data and a robust quantitative approach to demonstrate the limitations of mechanical-compaction-based basin models and emphasises the importance of thermally-driven mineralogical processes.

[24] Disintegration of the formation adjacent to the borehole wall creates a loose mix of formation materials including rock and mud derived from the formation during hydraulic failure that is supported by overpressured porewater. It has no structural strength (physical integrity). The process is likened to the shattering of material when impacted but while immersed in subsurface fluids (aqueous and hydrocarbon) and drilling mud, and of course, in the subsurface. Deeper into the formation, away from the borehole, fractures become less numerous but better organised geometrically; the longer the duration of pressure ≥FPP, the greater the depth to which disintegration of the formation occurs. Borehole geometry in the interval where fracturing occurs, is highly irregular and possibly cavernous.

It is inappropriate to "point the finger" at Waples specifically, as in his paper he represents a large body of thought and industry practice that still assumes that predicting pressure-evolution in basin models is predominantly controlled by mechanical compaction, independent of temperature. Ironically, Waples (1998) states "while it is true that where pressure data are available, a fluid-flow model can always be optimized to give the observed pressures, this success does not prove the optimized model is correct." The frustration in this statement is clear, but in the same volume, Waples and Couples (1998) seek solutions in the same mechanical realm where (Waples 1998) already documented the limitations. The solution to the prediction of pore pressure, as demonstrated by the GZ concept and independently by Giles et al. (1998), is to incorporate thermally-driven processes into basin models. This ensures, to quote Waples (1998) that "all processes relevant to pressure in the model" are included and that "accurate values of the critical parameters" are provided.

Following concepts used to define the Golden Zone (GZ), one can predict reservoir pressures from temperature and use probability distributions relevant to the study area. According to Nadeau (2011b) this requires,

a) estimation of the geothermal gradient from reservoir (interval) depth maps and temperature measurements;

b) estimation of the temperature at the seafloor;

c) creation of regional isotherm maps and use of the probability distributions to produce uncertainty maps.

Statoil have used this workflow on global exploration basin-screening evaluations, together with estimations of key isotherms (e.g. 60°C and 120°C – top and base GZ) and accompanying uncertainty maps based on relevant statistical data (Steen and Nadeau 2007; Nadeau and Steen 2007). To the best of my knowledge, the algorithms used by Statoil are not in the public domain.

When using large populations of subsurface data to make predictions at specific locations, care should be taken to ensure that data from "near-neighbour" wells (<10 km from prediction location) do not conflict with interpolated geothermal-gradient data from regional data sets. If "near neighbour" data do deviate from regionally-based data, the reasons for this require careful investigation, and when confident of the veracity and relevance of the "near neighbours" to the prediction location, they should be used to support the prediction rather than the regional data (Nadeau 2011b). This procedure ensures that relevant local geological information does not become diluted in a larger body of less relevant data.

Summary Severe well-control problems occur when strata with low confining rock-stress and high pore-pressures are drilled. Such formations are characterized by (anomalously) low LOP's. Failure to recognize the significance of low LOP's will result in overestimation of the rock strength and possible disintegration of the formation during drilling. Huge mud losses may ensue. If mud weight then is decreased to alleviate mud losses, a pressure kick or a blowout becomes more likely. According to the literature, the prediction of pore pressure at T >60°C using mechanical compaction models are unreliable, despite which the models continue to be used routinely. Thermally-driven models for pore-pressure evolution offer an improved modelling method.

EXPLORATION DRILLING IN UNSTABLE SUBMARINE STRATA: THE GEOLOGICAL CONTEXT OF THE MACONDO 252 #1 WELL

Drilling hydrocarbon exploration wells on unstable ocean-floor environments such as submarine slopes is commonplace, and has many important implications for the global exploration of modern-day deepwater hydrocarbon provinces. The Mississippi Canyon, and specifically slump-scars within the canyon, are areas where cognizance of present-day dynamic geological-processes are particularly relevant to safe and environmentally-responsible oil-industry drilling practice.

Slump-scars in the Mississippi Canyon: a unique geological context for hydrocarbon exploration drilling?

With respect to the Macondo 252 #1 disaster, McGee (2010) stated that "the local morphology of the sea floor combined with the occurrence of the April 2006 earthquake seems to indicate that sea-floor instability is active within 20km of the Deepwater Horizon site" and further "it is concluded that a combination of these factors contributed to the difficulties experienced while trying to control the well and its subsequent blowout." McGee's statements regarding seafloor instability are demonstrably correct, but no direct evidence is presented that may lead one to assign how any of the information he presents could contribute to cause the Macondo 252 #1 disaster. To examine whether the various geological features that contribute to seafloor instability described by McGee and others from the Mississippi Canyon seafloor have geologic cause that may have influenced the elevated pore pressures in Macondo 252 #1 and led to the disaster, one must understand the relationships between the seafloor and the subsurface. Of specific interest is that the unstable seafloor is characterised by large submarine slumps that are associated with small-magnitude earthquakes, hydrocarbon seeps and the occurrence of gas hydrates.

Submarine slumps[25] Many on-going research programmes globally (AAPG Bulletin, June 2004) study modern continental margins, and submarine slumps are common features of this research. Slumping is driven by gravitational instability that in turn may be driven by underlying tectonic movements, halokinesis or gas-hydrate instablilty. Some of the research is associated with the knowledge or potential of continental margins as major targets for hydrocarbon exploration and field development, and the associated environmental impact of those activities; they are intensely researched. During the past decade technological advances enabled significant enhancement of the study of continental margins that were previously impossible to visualise (Sager et al. 2004a). A specific advance has been the detailed mapping of very-large submarine slumps - the existence of which was already well-known. In the same areas, hydrocarbon gas and oil seeps, seafloor presence of gas hydrates and "cold-seep" biological communities are commonly observed (Childress et al. 1986; Milkov 2004; Sassen et al. 2004).

[25] Submarine slumps and slides have similar genesis and are difficult to differentiate, forming a continuum of related geological features. Both form on gravitationally unstable slopes and involve a down-slope movement of sediment. Slides tend to differentiate from slumps by involving more consolidated sediment units with less internal deformation generated during the slide. In contrast slumps are less consolidated and tend to have substantial internal deformation. These may be difficult to differentiate on modern seafloors as internal features may be hidden or indistinct. Slides may contain elements of slumps and visa versa (e.g. Færseth and Sætersmoen 2008).

The Mississippi Canyon has been a globally-significant area for continental margin/submarine slope research for at least 25 years (Salvador 1987; Brooks et al. 1987; Kennicut et al. 1988). This research remains active, including monitoring of seismicity, ocean-floor ROV surveying and remote semi-permanent ocean-floor monitoring sites (Sager et al. 2004b; Lee and George 2004; Tripsanas et al. 2004a,b). Large-scale slumping began forming the Mississippi Canyon ~17000 years ago (Behrens 1985) during the latest Pleistocene lowstand, when sea level was more that 100 meters lower than it is today. Today's canyon is believed to have been formed by a series of major slumps that have caused 1500 to 2000 km^3 of sediment to move down-slope and leave gaps in the slope that is the site of the present canyon (Hardin 1987 in Nadeau 2011b). Irregular seismicity is well known (Figure 14; **PWRPT5**) and in 2006, two events with magnitudes of 5.2 and 6.0 occurred. In general the earthquakes are small magnitude events and occur shallow (<5km) in the earth's crust; hence, the association with shallow processes such as slumping. Eight recent events have been recorded from the Mississppi Canyon area, seven of which have occurred since 1986 (Figure 14). It is likely that the earthquakes are the record of regional hydraulic fractures caused by sudden elevations of pore pressure.

Although episodes of slumping are seafloor geohazards that can damage installations, of more interest in the context of Macondo, is the relationship of slumps to subsurface pore-pressure that requires examination. In terms of understanding pore-pressure behaviour, large-scale slumps are significant because thick sediment-piles are moved from one location and dumped in another location further down the canyon. This reloading occurs in the period of time it takes for a slump to move (hours to days) and may involve very-rapid flow of debris (Parsons et al. (2000) in Parsons et al. 2004) estimate up to 120 ms^{-1} from 2-D numerical models). Examination of bathymetric maps of the GoM reveals that individual slumps may remove 10's to 100's m thickness of sediment that disperses into thinner units over larger areas down-slope when redeposited. In the area from which sediment is removed, there is an instantaneous reduction in lithostatic pressure in the underlying strata while the hydrostatic pressure remains constant. The effect is an instanteous shiftling of the lithostatic gradient to lower pressures thus moving closer to the hydrostatic gradient (Figure 15; **PWRPT22**). Consequently, in underlying intervals where the two gradients are already converging (i.e. slightly overpressured), an unloading-induced convergence can initiate hydraulic fracturing[26]. In Figure 15c formations **A** and **B** are both susceptible to collapse and a cause of mud losses. Equilibration of the excess pressure in **A** and **B** takes place in nature by drainage of fluids along fractures to the seafloor (MacDonald et al. 1996, 2000). If penetrated during drilling formations such as **A** and **B** will be subject to extensive formation damage and conditions for blowout become likely.

In areas where the sediment overburden is thickened by slumping, the instantaneous loading may cause localised liquefaction and fluidization in the very shallow subsurface (to 10's m depth). Thickening the sediment pile effectively buries the underlying strata and

[26] Although slumping is typically a rapid process (geologically instantaneous) the subsurface changes caused by unloading and loading of sediment vary in response time. Shallow processes such as liquefaction and fluidization directly below slumps are approximately concomitant with slumping. Timing of the initiation of deep hydraulic fracturing (in the GZ) is unknown but by analogy with similar processes during sand injection is likely to take days to months to propagate and can create permeable pathways through otherwise low-permeability strata that flow for millions of years (Vigorito and Hurst 2010). Re equilibration of pressure and thermal gradients following slumping is believed to take 1000's of years.

places them into slightly higher temperature regimes. It is conceivable that this deepening and heating of strata may enhance thermally-driven mineral reactions, change the rock-physical properties, and possibly accelerate pore-fluid expulsion. This process is likely to take millions years to have significant effect (Walderhaug et al. 2001; Ehrenberg et al. 2008a), and thus any significant direct influence on pore pressure in shallower levels in the 17,000 year period since formation of the Mississippi Submarine Canyon is unlikely.

Hydrocarbon seeps Seafloor seepage of gas and liquid hydrocarbons are well known along the continental margin of the northern Gulf of Mexico (Figure 16; **PWRPT7**; Geyer and Sweet 1972). Abrupt changes in seepage rates are recorded by temperature fluctuations proximal to the seeps (seafloor temperature in the Mississippi Canyon is typically <5°C) and are associated with seafloor fractures, and at least one large (50 m wide) crater (MacDonald et al. 2000). Crater formation is diagnostic of eruptive emission of fluid at the seafloor caused by a sudden elevation of pore pressure prior to release, similar to the formation of marine pockmarks (Hovland et al. 2002). MacDonald et al. (2000) recorded mean temperature elevation of 26.1°C with a maximum of 48.3°C associated with oil expulsion from which a deep origin for the oil is inferred (48.3°C equates to an origin from >2.5 km below the seafloor – likely to be hotter and deeper as no account is taken of cooling of the oil during seepage). The eruptive nature of the seeps and the associated high temperatures are indicative of rapid oil migration along open fractures; note that mud is transported with the hydrocarbons and forms a mud volcano on the seafloor. The mud is probably derived from hydraulic fracturing and erosion of mud-rich strata during hydraulic fracturing. The pulsed record of seepage is indicative of fluctuating pore-pressure that will determine the degree of fracture dilation. Similar pulsed-flow is inferred and observed for the extrusion of fluidised sand onto seafloors from regionally-developed hydraulically-fractured strata (Vigorito and Hurst 2010).

In the context of Macondo 252 #1 there are several interesting factors associated with natural hydrocarbon seeps:

1) hydrocarbon fluids and mud are expelled from the seafloor at high rates (similar to some commercial oil wells) over long periods of time;

2) a network of connected open-fractures persists as active fluid-migration conduits that link the seafloor with deep, hot sources of hydrocarbon fluids – a network that transects >>2 km of vertical section;

3) elevated temperatures are coincident with high oil-expulsion rates.

Because fluids cool as they rise toward the surface, the 48.1°C maximum temperature associated with oil expulsion (MacDonald et al. 2000) is cooler than its temperature at the point of origin, indicating that the oil originated at least ~2.5 km below the seafloor and in strata that were most likely to be in the upper part of the Golden Zone (>60°C). Note, that the Macondo 252 #1 reservoir temperature is 117°C (footnote 3) which is indicative of a location near the base of the GZ, immediately above the transition between the *accumulation* and *expulsion zones*. The open natural-fracture system and expulsion of mud record the presence of pervasive hydraulic fractures and a large volume of strata at depth with elevated pore pressure that can maintain fracture dilation.

Triggering of large-scale hydraulic fracturing requires that subsurface pore-pressure exceeds the leak-off (LOP) and/or fracture propagation (FPP) pressures (Figure 13; **PWRPT18**). It is implicit that the pore pressure has to approach lithostatic pressure, locally exceed it and persist (to the present day), to allow fluid seepage. A “regional store” of overpressured fluids is requisite to this process and, because hydrocarbons are seeping, the fractures must originate where large volumes of hydrocarbons are available. By combining our knowledge of the slump-history of the Mississippi Submarine Canyon with that of the Golden Zone, an attractive and plausible coupled model for regional-scale hydrocarbon seepage is developed. The relevance of this model to drilling practice can then be considered.

Coupling of slumps and seeps - prediction of drilling hazards Unloading of the strata below successive slump-scars (Figure 15; **PWRPT22**) causes slightly over-pressured rock units to become more susceptible to hydraulic fracturing (Figure 17; **PWRPT23**). In the case of the Mississippi Canyon, we know that the hydraulic fractures that seep hot crude-oil at the seafloor (MacDonald et al. 2000) propagated from deep (>2.5 km) hydrocarbon-saturated strata (a statistically-high probability of being in the Golden Zone, Figures 7 and 9; Ehrenberg et al. 2008a), so an obvious coupling is made with unloading. With each episode of slumping, a new unloading occurs thus perpetuating the hydraulic fracturing and weakening a larger volume of rock within the Golden Zone. The pervasiveness of the hydraulic fracturing is related to the areal extent of the slump scars, an area that can be mapped using seafloor imaging methods (Sager et al. 2004). The high sustained flow rates of oil at the seafloor indicate that a large volume of elevated pore pressure is present.

When exploration boreholes drill into intensely fractured formations, significant losses of drilling mud are expected, assuming that the mud weight exceeds the pore pressure. If, however, boreholes are drilled where fracturing of the formation is intense and regionally developed, as one would expect below the area of the Mississippi Canyon slump scars, the low physical integrity will cause it to disintegrate and the elevated pore pressure will vent fluids to the surface via the borehole. In the absence of an appreciation of the thermal control of subsurface pore-pressure above 60°C, and the probable influence on formation integrity caused by slump-initiated unloading, the likelihood of encountering severe drilling problems in some areas of the Mississippi Canyon area are likely to be very high.

Summary The Mississippi Canyon is an area characterised by unstable seafloor conditions. Irregular seismicity is associated with very-large-scale slumping that has been active for 17.000 years and associated large-scale hydraulic fracturing. Active hydrocarbon seeps are very common including >40°C oil at rates >100 barrels/day. Seeps emanate from hydraulic fractures that reach the seafloor and are connected to hydrocarbon-rich strata at depth (>2.5km). Hydraulic fractures formed as a response to sediment unloading during slumping. Generation of hydraulic fractures at depth weakened strata (low confining-stress) that initiated leakage of oil to the seafloor and remained susceptible to further physical disruption and possible disintegration when drilled.

Are the drilling problems encountered in Macondo unique to a restricted area of the Mississippi Canyon?

In the Introduction the question was posed “whether the geological conditions in this area of the Mississippi Canyon are unique in terms of their potential affect on hydrocarbon-borehole drilling and thus unlikely to foresee or predict ....” within the Mississippi Submarine Canyon (certainly within areas where major slumps occur) and elsewhere globally where similar geological conditions exist – provided that similar drilling practices were employed elsewhere. Given the preceding technical evaluation where geological factors have obvious affect on overpressure and borehole stability the contention that the Macondo geological conditions are "commonplace, a circumstance that would make geological understanding of only marginal relevance to design of a drilling programme," is unlikely.

The preceding section makes a strong case for a geologically-predictable occurrence of severe drilling problems in the area of the Macondo disaster that is supported by substantial scientific and technical literature and public-domain data. In the absence of knowing whether the team operating the Macondo well was aware or not of the underlying considerations described in the preceding text, the disaster that occurred presents an opportunity to ensure that similar unsuccessful practice is avoided. Nadeau's (2011b) evaluation of leak-off pressures (LOP's) in the US GoM shows the presence of a significant number anomalously low LOP's particularly for offshore Louisiana (Figure 11; **PWRPT20**)[27] and 75% of the anomalously low (<1.7 g/cm^3) mud gradients at more than 3 km sub-seafloor from offshore Louisiana occur in the Mississippi Canyon area (Figure 12; **PWRPT20**). These data show that low-stress regimes exist in the sub-surface GoM, which if they are affected by high fluid-pressures as predicted by the GZ concept, will increase risks to drilling and well completion operations because of the propensity to cause destabilization of formations adjacent to the borehole by hydraulic fracturing. If the weight of drilling mud sustains down-hole pressure above FPP (Figure 13; **PWRPT18**) for an extended period, damage to the formation will become so extensive that well repair becomes impractical if not technically impossible.

In the light of the information reviewed in this report, and with specific focus on the area of the Mississippi Canyon, a simple improvement in drilling practice focused on drilling safety can, and should, be made. This should include careful evaluation of LOP's and mapping the distribution of the 60°C and 120°C isotherms (the Golden Zone) so enabling better predictive modelling of overpressure distribution.

Uniqueness? As slumps are common features of continental margins and many of these overlie actual or prospective hydrocarbon systems, there is no reason to believe that the geological conditions in the Mississippi Submarine Canyon are unique. For example, the Storegga Slide on the Atlantic coast of mid Norway is arguably the most studied, largest and best-known analogue for all giant submarine slumps and slides. Known since 1978, it was first described in detail by Bugge (1983) who estimated that 5580 m^3 of sediment was displaced, although more modern estimates suggest a smaller volume (up to 3200 m^3, Parsons et al. 2004). Storegga lies beneath 800-1100 m of water and overlies part of a major gas-prone hydrocarbon province that includes the giant Ormen Lange gas field (discovered by Norsk Hydro, Shell, Statoil, BP, ExxonMobil in 1997) and is currently interpreted as a single multi-phase slide that occurred ~8150 years ago. It overlies more ancient slides, thus recording a long history of slope instability (Evans et al. 1996; Færseth and Sætersmoen 2008).

When planning the development of Ormen Lange, a huge amount of surveying and modelling of the Storegga Slide was undertaken by oil companies and independent bodies

[27] LOP's with values <1.7 g/cm^3 equivalent mud-weight gradients are of concern for drilling operations (Nadeau 2011b). At depths >3km subsea in offshore Louisiana anomalously low LOP's are common.

to evaluate whether development of the field would cause severe destabilisation of the continental margin, cause tsunamis and devastate the marine environment. The modern seafloor is highly irregular and has common methane seeps and gas hydrate accumulations much in common with the Macondo seafloor area and other parts of the continental margin of the northern Gulf of Mexico[28]. At the time of drilling development wells on Ormen Lange, it was considered to be one of the most challenging drilling programmes ever undertaken (Drilling Contractor 2007). Although the unstable seafloor and weak rock-strength are an ongoing challenge for drilling and have caused delays, no serious safety or environmental problems similar to Macondo are recorded despite similar, arguably more severe operational conditions.

There is a lack of evidence for the site of the Macondo 252 #1 being geologically unique in the GoM. Ehrenberg and Nadeau (2008) and Nadeau (2011b) show that there is substantial evidence from drilling history that a significant area of the Louisiana continental margin, and specifically the Mississippi Canyon is known to have low-stress regimes (Figures 11 and 12) that are recorded by anomalously low leak-off pressures (LOP's). In light of this, it is wise when drilling on any global continental margin in and adjacent to slump scars to map and consider the origin and significance of any seafloor hydrocarbon (in particular oil) seeps and to map the distribution of the Golden Zone. I concur with Nadeau (2011b) that to include thermal data in the modelling of pore pressure will greatly enhance safer and more economically-effective drilling practice. As the necessary data to carry out this modelling on the GoM are in the public domain, there is no reason why the practice should not be widely adopted.

Summary It is very unlikely that the drilling problems in Macondo 252 #1are unique, as the geological conditions there are not unique within the GoM or elsewhere. It is very likely that other wells located in the Canyon's slump scars would behave similarly. As large submarine slumps and slides are common features of many hydrocarbon provinces conditions similar to those encountered in Macondo 252 #1 and more generally in the vicinity of the Mississippi Canyon are expected to occur. Immediate steps that can be taken to minimise the chance of a recurrence of a "Macondo-type" incident include mapping of the Golden Zone and incorporating thermal relationships in pore-pressure modelling, detailed of LOP's in adjacent wells and evaluation of seafloor hydrocarbon-seeps.

[28] Storegga should not be construed to be "identical" to the Mississippi Submarine Canyon slumps. For example, it is substantially larger, it is not fed and modified by a present-day river system, insignificant modern shallow-seismicty is known and the major gravitational movement appears to have stopped.

HPHT DEFINITION: GLOBAL LEARNING FROM MACONDO 252 #1

HPHT came into use following publication of the Cullen report on the Piper Alpha platform disaster (1988). Since Piper Alpha, HPHT has evolved as oil companies seek to discover hydrocarbons in increasingly deep, hostile subsurface environments. Schlumberger's oilfield glossary states that in the UK HPHT (High Temperature High Pressure) is defined as a well that has an undisturbed bottom-hole temperature greater than 149°C (300°F) and pore pressure of at least 0.8 psi/ft. The definition is extended to requiring a Blowout Preventer (BOP) with a rating in excess of 10,000 psi (68.95 MPa[29]). Three HPHT categories are defined based on the stability limits of common well-service-tool components such as elastomeric seals and electronic devices: HPHT, Ultra-HPHT and HPHT-hc, the latter having no current significance (in 2008) to hydrocarbon drilling. Interestingly the definitions of HPHT are defined by materials and technology tolerances at elevated pressures and temperatures rather than by the thermal and pressure characteristics of the rocks being drilled (DeBruijn et al. 2008).

These technology-led HPHT definitions are to enable appropriate technology design and development to allow drilling in extreme conditions at absolute temperature and pressure (T and P) conditions. They are not a direct response to the prediction of likely T and P changes that are influenced by geological characteristics during drilling. Specifically, knowledge of the absolute pressure in MPa (Figure 18; **PWRPT21**) is of little relevance to drilling if the depth at which it occurs is unknown. Hence, without depth reference they cannot be used to predict rates of change of pressure; for example, sudden elevations of pore pressure that may lead to hydraulic fracture of low-stress formations. Remembering that geologists provide the prognoses for wells that are the basis for the engineering solutions that will allow safe, low-environmental impact and cheap-as-possible drilling, it is more appropriate if HPHT definitions relate directly to temperature and pressure gradients and not to tolerances associated with technology-failure margins. With reference to pore pressure, sudden increases are very important to predict. The relationship between isotherms and pore pressure are demonstrated earlier and are fundamental to understanding and using the Golden Zone concept to improve safe drilling practice.

A pragmatic definition of HPHT conditions that is entirely geologically consistent for the Gulf of Mexico uses the statistically-robust reservoir T and P data from Ehrenberg et al. (2008a, 11,864 reservoir data points) and led Nadeau (2011b) to propose the onset of HPHT as >1.4 g/cm^3 specific gravity equivalent gradients (equivalent to ~>12 ppg mud weight) and >120°C (Figure 19; **PWRPT17**) rather than the industry definitions (149°C and ~15 ppg or 1.7 g/cm^3 specific gravity-equivalent gradients, Schlumberger Oilfield Glossary 2011). Setting a geologically-appropriate boundary for the onset of HPHT conditions has specific relevance to pore-pressure prediction because in many global geological settings, as documented it is not absolute T or P conditions that may cause drilling problems (Bjørkum and Nadeau 1998; Bjørkum et al. 1998; Nadeau et al. 2002, 2005; Buller et al. 2005; Ehrenberg and Nadeau 2005; Ehrenberg et al. 2007; Ehrenberg et al. 2008b; Nadeau 2011a), but the exponential rates of increased cementation at >120°C.

[29] MPa = megapascals is the SI uiut for force per unit area. 1 MPa = 145.04 pounds-force per square inch (lbf/in^2).

In the GoM many occurrences of >1.7 g/cm^3 specific gravity reservoir pressure (reservoir overpressure) conditions occur below 149°C (Figure 19). Hence if 149°C is applied as the lower cut-off for HPHT conditions, as opposed to 120°C, it means that 1-2 km of drilling (depending on the geothermal gradient) in which reservoir overpressure is a common occurrence will be inferred to be sub-HPHT conditions; presumably less liable to cause drilling problems. This assumption could lead to misconceptions about drilling conditions and safety. Of even more consequence in terms of drilling safety are the specific formation characteristics that may be encountered in the 120-149°C temperature window and in particular in geologically "young" Miocene (~ <23 Ma) and more recent strata.

In the GoM where rates of sediment deposition and burial are high (Nadeau 2011), Miocene and younger rocks have entered the *accumulation zone* (Golden Zone) and *expulsion zone* (geologically) recently. Cementation processes in both mudstones and sandstones will often not have had time to go to completion[30] and consequently the rocks will often retain loose granular character that is physically weak and prone to disaggregation during drilling (characterized by low LOP's[31]). Where these strata occur in the 120-149°C temperature window they constitute a problematic combination of low rock-strength and susceptibility to overpressure BUT at temperatures (and drilling depths) below industry-recognized limits for HPHT conditions (Schlumberger Oilfield Glossary 2011). Unexpected and exponential changes in pore pressure may be encountered as temperature increases above 60°C,

Summary Technology-led HPHT definitions that use material stabilities at absolute temperature/pressure (T/P) conditions are probably inappropriate for defining geological HPHT conditions and where and when overpressure occurs. Geological definition of HPHT requires T/P gradients. If the onset of HPHT conditions is set too deep significant pore pressure anomalies and problematic drilling scenarios will not be effectively predicted. Geologically-young formations (Miocene (~ <23 Ma) and younger) are particularly susceptible to low rock strength and overpressure in the temperature window between 120-149°C.

[30] "time to go to completion" – mineral reactions are initiated at specific temperatures but the dissolution and growth of minerals is not instantaneous. For example, as shown by Walderhaug et al. (2001) quartz cementation is sandstone increases exponentially with increased T and may take 10Ma to complete.

[31] Nadeau (2011b) reports that if in offshore Louisiana operations petroleum engineers and geoscientists assume that low LOP's are routine, they may have overlooked or underestimated the possible deleterious implications for drilling operations in low subsurface stress-regimes.

LOP's[26]

LOP's (leak off pressures) are routinely acquired during the drilling of wells. By definition, (http://www.glossary.oilfield.slb.com) they measure "the magnitude of pressure exerted on a formation that causes fluid to be forced into the formation." The tests are done to determine the physical integrity of formations. The fluid being forced into the formation may flow into porous media (reservoirs) or fracture less-permeable formations. A real-time record of volume of injected fluid vs. fluid pressure is obtained. Initially, the plot approximates to a straight line and the "leak off" is when "a point of permanent deflection" from the straight line occurs. Leak-off tests are an important input to well design and help to determine whether a specific design is sufficiently conservative.

"Sufficiently conservative" is poignant as if severe problems completing or controlling wells occur, these are a strong indication that well design was insufficiently conservative. In a geological context, LOP's are important to understand as they are a direct measure of the physical stability of a formation, in particular indicating their tendency to fracture. Tendency to fracture relates directly to the presence of subsurface low-stress regimes, which appear to be common in the Mississppi Submarine Canyon (Nadeau 2011a). Failure to incorporate and understand LOP's in a geological context may lead or contribute to serious well safety problems.

Summary If failure to recognize the significance of low LOP's is a shortcoming of current industry practice that can lead to serious safety and environmental concerns, as well as direct and indirect economic problems, this needs to be addressed. The background for Mississippi Submarine Canyon operations presented in Nadeau (2011b) raises serious concerns that appear to have a direct influence on formation integrity during drilling. Nadeau suggests redefining the lower limit of HPHT drilling conditions in line with geological considerations and drilling history, which from my evaluation of current practice, is worthy of immediate attention. Assuming the global relevance of the GZ concept, the implication is that much greater effort within the oil industry to share drilling experiences and relevant data from "problematic" HPHT wells will benefit industry partners and secure safer and more effective drilling practice.

CONCLUSIONS

There is a huge body of geological literature relevant to the Mississippi Submarine Canyon, in which Macondo is located. The literature is diverse and contains applied and academic geological public-domain information, some directly related to oil industry themes, and others most definitely not. As well as being of obvious interest from the perspective of oil and gas exploration, another pervading theme is the association between the Canyon and seafloor instability. The relationships between seafloor instability and subsurface geology have an immediate relevance to prognosis of the physical properties likely to be encountered during drilling. Intimately linked with these prognoses are methods to predict where and at what depth(s) during drilling overpressure will occur and what the scale of the overpressure will be. Both issues are typically addressed in geological well-prognoses that are made prior to drilling. Prediction of overpressure is notoriously difficult (Waples 1998), but there appears to be a substantial disconnect between the way in which pore pressure is predicted and the processes that actually control pore pressure at temperatures >60°C. The disconnect is alarming because it appears to ignore substantial geological literature and contradicts subsurface reservoir data. It may be contributing to unsafe drilling practice and related environmental impact.

The long history of successful drilling along the northern continental margin of the Gulf of Mexico (GoM) is testimony to the success of geological prognosis of subsurface conditions. In that context, it is surprising to learn that conventional pre-drill prediction of overpressure development is rarely successful (Nadeau et al. 2005; Nadeau 2011b). If Nadeau is correct, this is alarming given the availability of public-domain offshore, subsurface data from the GoM that should be ideal to underpin predictive subsurface models. The potential of the GoM offshore data for enhancing predictive modelling is demonstrated by the successful modelling of pore pressure using thermally-driven models (above 60°C) (Nadeau et al. 2005; Ehrenberg et al. 2008a; Nadeau 2011).

Thermal control over pore-pressure development during progressive burial is a recurring theme in many papers from Statoil authors that culminated in a general overview of their work and use of the term Golden Zone (GZ) in Buller et al. (2005). Subsequently Statoil authors have published more accounts that verify, use and describe the GZ concept. An impressive feature of the GZ concept is that it is underpinned by a huge public-domain database that is hence equally available to any company or individuals. In the absence of any public domain offerings from other oil companies, it is impossible to ascertain whether similar heavily-data-dependent concepts are in use elsewhere and whether the significance of thermally-driven mineral reactions is recognised and incorporated into basin models (examples of possible exceptions are Giles et al. 1992, 1998). Importantly, the GZ concept incontrovertibly identifies that: 1) >90% of the Earth's light hydrocarbons are reservoired in a thermal window between 60 and 120°C (the Golden Zone); 2) porosity and permeability reduction at >60°C is caused by thermally-driven mineral reactions that are entirely predictable and quantifiable; 3) hydraulic fracture of strata occurs in response to elevation of pore pressure above the hydrostatic gradient.

If then the GZ concept and its implications for the elevation of pore pressure above the hydrostatic gradient are ignored, what may the consequences be?

1) Should one rely on basin-modelling procedures that use mechanical compaction as the control mechanism on pore-pressure evolution while knowing that these procedures are not fit-for-purpose (e.g. Waples 1998)? Why are they still used if they can only make accurate predictions with the benefit of hindsight?

2) Why in the face of abundant evidence for mineralogical thermally-driven controls on pore pressure are basin models not incorporating these effects? In particular why ignore the results of successful basin models that do incorporate thermal effects (Nadeau et al. 2005)?

3) In the offshore GoM, with its huge publically-available data base (Ehrenberg et al. 2008a), is there an industry-wide access and use of these data to help ensure safe and optimal drilling practice?

Nadeau (2011b) describes a very limited use of leak-off pressures (LOP's) for helping to constrain drilling risk and to predict subsurface behaviour when drilling encounters formations with low confining rock stress. He calls for an industry-wide effort to collect and disseminate all relevant records related to drilling low-stress formations on GoM as part of an effort "to facilitate the rapid development of technical expertise and operational practice" with the aim of reducing "the risks of future safety incidents and harm to marine and related environments." There is no evidence that the drilling community has grasped the potential importance of mapping where formations with low confining stress occur – in my opinion this is a priority.

A similar very practical issue is how HPHT drilling conditions are defined and how that may influence drilling practice. Industry-standard HPHT definitions (DeBruijn et al. 2008) are based on material tolerances of absolute T and P; absolute values of T and P are not critical in the prediction of overpressure. T and P gradients are however critical to understand. Hence, definition of HPHT environments has to retain geological significance as after all the drilling materials are interacting with rocks!

My report is compiled in the absence of specific knowledge of what procedures oil companies operating in the Mississippi Submarine Canyon follow when creating a prognosis of the conditions to be encountered in a new well. There is, however, an abundance of public-domain data relevant to the prediction of pore pressure.

1) Oil is known to seep at high rates and high T (>40°C) from fractured seafloor, implying that the oil has flowed quickly from depth (>2.5 km and probably substantially more) where oil-filled formations charge the seeps. Implicitly one must infer that the fractures connect between the oil-filled strata and the seafloor and that they formed by large-scale hydraulic fracture in response to elevated pore pressure.

2) Slump scars indicate that in some locations 100's of meters of sediment have detached and moved down-slope. In doing so they have removed physical load from the underburden that creates a mechanism that could trigger hydraulic fracture at depth, in particular in formations in which pore pressure was already above the hydrostatic gradient. The hydraulic fracture may be a cause of local seismicity recorded in the area (last in 2006).

3) LOP's from the Mississippi Canyon indicate that formations with low confining stress occur adjacent to Macondo (Nadeau 2011b). These data are an indication that problems with formation integrity during drilling are likely.

When one adopts the GZ concept that predicts pore pressure from geothermal gradients above 60°C a geological cause and effect for pore pressure elevation and large-scale hydraulic fracturing is developed.

Just by working with public domain data and becoming familiar with possible shortcomings in oil-industry practice (Nadeau 2011b) a good case can be made for prediction of “anomalous” drilling conditions where high mud-loses and risk of a subsequent blow-out occur in the area of the Mississippi Canyon where Macondo is located. These conditions are extremely unlikely to be specific only to this area and will have a significant probability of occurring along other continental margins where major slumps occur above active petroleum provinces. I conclude that the geological conditions in the Mississippi Submarine Canyon are not unique but symptomatic of conditions elsewhere. This is encouraging as if appropriate data and use of data are applied, the inherent technical risk when drilling in similar environments can be better constrained.

Andrew Hurst

Professor Andrew Hurst

August 19, 2011

APPENDIX A

REFERENCES LIST

AAPG Bulletin 88, (2004) Special theme issue: high-resolution studies of continental margin geology and geohazards.

Aase, N.E., Bjørkum, P.A. and Nadeau, P.H. 1996. The effect of grain-coating micro-quartz on preservation of reservoir porosity. AAPG Bulletin 80, 1654-1673.

Behrens, E.W., 1984, Unifite Muds in Intraslope Basins, Northwest Gulf of Mexico. Geo-Marine Letters, 4, 227-233.

Bjørkum, P.A. 1996. How important is pressure in causing dissolution of quartz in sandstones? Journal of Sedimentary Research 66, 147-154.

Bjørkum, P.A. and Nadeau, P.H. 2008. Temperature controlled porosity/permeability reduction, fluid migration, and petroleum exploration in sedimentary basins. Australian Petroleum Production and Exploration Association Journal 38, 453-464.

Bjørkum, P.A., Oelkers, E.H., Nadeau, P.H., Walderhaug, O. and Murphy, W.M. 1998. Porosity prediction in sandstones as a function of time, temperature, depth, stylolite frequency and hydrocarbon saturation. AAPG Bulletin 82, 637-648.

Bjørlykke, K. 1984. Formation of secondary porosity. How important is it? In: Clastic Diagenesis, Macdonald, D.A. and Surdam, R.C. (eds), AAPG Memoir 37, p. 285-292.

Brooks, J.M., Kennicutt II, M.C., Fisher, C.R., Macko, S.A., Cole, K., Childress, J.J., Bidigare, R.R. and Vetter, R.D. 1987. Deep sea hydrocarbon seep communities: evidence for energy and nutritional carbon sources. Science 238, 1138-1142.

Buller, A.T., Bjørkum, P.A., Nadeau, P.H. and Walderhaug, O. 2005, Distribution of hydrocarbons in Sedimentary Basins. Research & Technology Memoir No. 7, Statoil ASA, Stavanger, 15 p.

Burst, J.F. Jr. 1969. Diagenesis of Gulf Coast clayey sediments and its possible relation to petroleum migration. AAPG Bulletin 53, 73-83.

Childress, J.J., Fisher, C.R., Brooks, J.M., Kennicutt II, M.C., Bidigare, R.R. and Anderson, A.E. 1986. A methano-trophic marine molluscan (bivalvia, mytilidae) symbiosis: mussels fuelled by gas. Science 233, 1306-1308.

DeBruijn, G., Skeates, C., Greenaway, R., Harrison, D., Parris, M., James, S., Mueller, F., Ray, S., Riding, M., Temple, L. and Wutherich, K. 2008. High-Pressure, High-Temperature Technologies. Schlumberger Oilfield Review, Autumn 2008, 46-60.

Drilling Contractor, 2007. Ormen Lange leads the way for North Sea innovation with big bore, deepwater gas wells. Paper at IADC World Drilling 2007, 19-20 June 2007, Paris. p. 44-47.

Ehrenberg, S.N. 1993. Preservation of anomalously high porosity in deeply buried sandstones by grain-coating chlorite: examples from the Norwegian continental shelf. AAPG Bulletin 77, 1260-1286.

Ehrenberg, S.N. and Nadeau, P.H. 2005. Sandstone vs. carbonate petroleum reservoirs: a global perspective on porosity-depth and porosity-permeability relationships. AAPG Bulletin 89, 435-445.

Ehrenberg, S.N., Nadeau, P.H. and Aqrawi, A.A.M. 2007. A comparison of Khuff and Arab reservoir potential throughout the Middle East. AAPG Bulletin 91, 275-286.

Ehrenberg, S.N., Nadeau, P.H. and Steen, Ø., 2008a, A megascale view of reservoir quality in producing sandstones from the offshore Gulf of Mexico. AAPG Bulletin 92, 145-164.

Ehrenberg, S.N., Aqrawi, A.A.M. and Nadeau, P.H. 2008b. An overview of reservoir quality in producing Cretaceous strata of the Middle East. Petroleum Geosciecne 14, 307-318.

Esrafili-Dizaji, B. and Rahimpout-Bonab, H. 2009. Effects of depositional and diagenetic characteristics on carbonate reservoir quality: a case study from the South Pars gas field in the Persian Gulf. Petroleum Geoscience 15, 325-344.

Evans, D., King, E.L., Kenyon, N.H., Brett, C. and Wallis, D. 1996. Evidence for the long-term instability in the Storegga slide of western Norway. Marine Geology 130, 218-292.

Færseth, R.B. and Sætersmoen, B.H. 2008, Geometry of a major slump structure in the Storegga slide region offshore western Norway. Norwegian Journal of Geology, 88, 1-11.

Garcia, O., MacDonald, I.R., Zimmer, B., Shedd, W. and Frye, M. 2009. Satellite SAR inventory of Gulf of Mexico oil seeps and shallow gas hydrates. Geophysical Research Abstracts 11, EGU2009, p. 11633.

Geyer, R.A. and Sweet, W.E. Jr. 1972, Natural Hydrocarbon Seepage in the Gulf of Mexico. Society of Petroleum Engineers (SPE), Symposium on Environmental Conservation, Lafayette, Louisiana. Paper # 4199-MS, 16 p.

Giles, M.R., Stevenson, S., Marton, S.V., Cannon, S.J.C., Hamilton, P.J., Marshall, J.D. and Samways, G.M. 1992. The reservoir properties and diagenesis of the Brent Group: a regional perspective. In: Geology of the Brent Group, Morton A.C., Haszeldine, R.S., Giles, M.R. and Brown, S. (eds), Geological Society of London Special Publication 61, p. 329-350.

Giles, M.R., Indrelid, S.L. and James, D.M.D. 1998. Compaction – the great unknown in basin modelling. In: Basin modeling: practice and progress, Duppenbecker, S.J. and Iliffe, J.E. (eds), Geological Society of London Special Publication 141, 15-43.

Gluyas, J.G. and Coleman, M. 1992. Material flux and porosity changes during sediment diagenesis. Nature 356, 52-54.

Gluyas, J.G., Robinson, A.G., Emery, D., Grant, S.M. and Oxtoby, N.H. 1993. The link between petroleum emplacement and sandstone cementation. In: Petroleum Geology: North-West Europe – Proceedings of the 4th Petroleum Geology Conference, Parker, J. (ed), Geological Society, London, p. 1395-1402.

Head, I.M., Jones, D.M. and Larter, S. R. 2002. Biological activity in the deep subsurface and the origin of heavy oil. Nature 246, 344-352.

Hoffman, J. and Hower, J. 1979. Clay mineral assemblages as low grade metamorphic geothermometers: application to the thrust faulted disturbed belt of Montana, USA. In: Scholle, P. and Schluger, P.R. (eds), Aspects of Diagenesis, SEPM Special Publication 28, p.55-79.

Hovland, M., Gardner, J.V. and Judd, A.G. 2002. The significance of pockmarks to understanding fluid flow processes and geohazards. Geofluids 2, 127-136.

Hower, J., Eslinger, E.V., Hower, M. and Perry, E.A. 1976. Mechanism of burial metamorphism of argillaceous sediments: 1. Mineralogical and chemical evidence. Geological Society of America Bulletin 87, 725-737.

Hubbert, M.K. and Willis, D.G. 1957, Mechanics of hydraulic fracturing. Trans. AIME, 210, 153-163.

Kennicutt II, M.C., Brooks, J.M. and Denoux, G.J. 1988. Leakage of deep, reservoired petroleum to the near surface on the Gulf of Mexico continental slope. Marine Chemistry 24, 39-59.

Lapham, L.L., Chanton, J.P., Martens, C.S., Sleeper, K. and Woolsey, J.R. 2008. Microbial activity in surfical sediments overlying acoustic wipeout zones at a Gulf of Mexico cold seep. Geochemistry, Geophysics, Geosystems 9, 17 p.

Lee, E.Y.-D. and George, R.A. 2004. High-resolution geological AUV survey results across a portion of the eastern Sigsbee Escarpment. AAPG Bulletin 88, 747-764.

Lothe, A.E., Borge, H. & Sylta, Ø., 2005, Evaluation of Late Cap Rock Failure and Hydrocarbon Trapping Using a Linked Pressure and Stress Simulator. In: P. Boult & J. Kaldi (eds.), Evaluating fault and cap rock seals. AAPG Hedberg Series, 2, 163-178.

MacDonald, I.R., Guinasso, N.L. Jr., Ackleson, S.G., Amos, J.F., Duckworth, R., Sassen, R. and Brooks, J.M. 1993. Natural oil slicks in the Gulf of Mexico visible from space. Journal of Geophysical Research 98, 16,351-16,364.

MacDonald, I.R., Reilly, J.F. Jr, Best, S.E., Venkataramaiah, R., Sassen, R., Amos, J.F. and Guinasso, N.L. Jr. 1996. A remote-sensing inventory of active oil seeps and chemosynthetic communities in the northern Gulf of Mexico. In: Schumacher, D. and Abrams, M.A. (eds) Hydrocarbon migration and its near-surface expression. American Association of Petroleum Geologists Memoir 66, 27-37.

MacDonald, I.R., Buthman, D.B., Sager, W.W., Peccini, M.B. and Guinasso, N.L. Jr. 2000. Pulsed oil discharge from a mud volcano. Geology 28, 907-910.

Marchand, A.M.E., Haszeldine, R.S., Macauly, C.I., Swenne, R. and Fallick, A.E. 2000. Quartz cementation inhibited by crestal oil charge: Miller deep water sandstone. Clay Minerals 35, 210

Marse, T. and Tsoflias, S.L. 2001. Geogenic inputs to the northern Gulf of Mexico airshed. 10th Annual Emission Conference, Denver. 6p.

McGee, T. 2010. Geologic characteristics in the vicinity of the Deepwater Horizon oil spill. 2010 IEEE/OES US/EU Baltic International Symposium (BALTIC). 25-27 August, 2020, Riga, Latvia. ISBN 978-1-4244-9227, 4p.

Miklov, A.V. 2004. Global estimates of hydrate-bound gas in marine sediments: how much is really out there? Earth Science Reviews 66, 183-197.

Nadeau, P.H. 1999. Fundamental particles: An informal history. Clay Minerals 34, 185-191.

Nadeau, P.H. 2011a. Earth's energy "Golden Zone": a synthesis from mineralogical research. Clay Minerals 46, 1-24.

Nadeau, P.H., 2011b. Earth's energy "Golden Zone concept for understanding overpressure development and drilling safety in energy exploration. Deepwater Horizon Study Group Working Paper – January 2011, 18p.

Nadeau, P.H., Wilson. M.J., McHardy, W.j. and Tait, J.M. 1984. Interstratified clay as fundamental particles. Science 225, 923-925.

Nadeau, P.H., Peacor, D.R., Yan, J. and Hillier, S., 2002a, I/S precipitation in pore space as the cause of geopressuring in Mesozoic mudstones, Egersund Basin, Norwegian Continental Shelf. American Mineralogist, 87, 1580-1589.

Nadeau, P.H., Walderhaug, O., Bjørkum, P.A. and Hay, S. 2002b. Clay diagenesis, shale permeability and implications for petroleum systems analysis. EAGE Annual Conference, Florence, Abstract G003.

Nadeau, P.H., Bjørkum, P.A. and Walderhaug, O., 2005, Petroleum system analysis: impact of shale diagenesis on reservoir fluid pressure, hydrocarbon migration and biodegradation risks. In: A.G. Doré & B. Vining (eds.), Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference, Petroleum Geology Conferences Ltd, Published by the Geological Society, London, 1267-1274.

Nadeau, P.H. and Steen, Ø. 2007. The thermal structure of sedimentary basins: Mapping the "Golden Zone" worldwide. Norwegian Geological Society, Winter Conference, Stavanger, Norway, NGF Abstracts and Proceedings, p. 67.

Oelkers, E.H., Bjørkum, P.A. and Murphy, W.M. 1996. A petrographic and computational investigation of quartz cementation and porosity reduction in North Sea sandstones. American Journal of Science 296, 420-452.

Oelkers, E.H., Nadeau, P.H., Bjørkum, P.A., Walderhaug, O. and Murphy, W.M. 1998. A closed-system four component model for computing the porosity and permeability of sedimentary basin sandstones, Goldschmidt Conference, Toulouse 1998. Mineralogical Magazine 62A, 1100-1101.

Oelkers, E.H., Bjørkum, P.A., Walderhaug, O., Nadeau, P.H. and Murphy, W.M. 2000. Making diagenesis obey thermodynamics and kinetics: the case of quartz cementation in sandstones from offshore mid-Norway. Applied Geochemistry 15, 295-309.

Parsons, B.S., Vogt, P.R., Haflidason, H. and Jung, W-Y. 2004. Seafloor reconnaissance and classification of the Storegga Slide headwall region, Norwegian Sea, using side-scan sonar, video, and photographs acquired on submarine NR-1. AAPG Bulletin 88, 841-855.

Sager, W.W., Bryant, W.R. and Dole, E.H. 2004a. Introduction: resolution is the solution. AAPG Bulletin 88, 699-701.

Sager, W.W., MacDonald, I.R. and Rousheng Hou 2004b. Side-scan sonar imaging of hydrocarbon seeps on the Louisiana continental slope. AAPG Bulletin 88, 725-746.

Salvador, A. 1987. Late Triassic-Jurassic palaeogeography and origin of the Gulf of Mexico Basin. AAPG Bulletin 7, 419-451.

Sassen, R., Roberts, H.H., Carney, R., Milkov, R.V., DeFreitas, D.A., Lanoil, B. and Zhang, C. 2004 Free hydrocarbon gas, gas hydrate, and authigenic minerals in chemosynthetic communities of the northern Gulf of Mexico continental slope: relation to microbioal processes. Chemical Geology 205, 195-217.

Schlumberger Oilfield Glossary 2011. http://www.glossary.oilfield.slb.com/

Schneider, F., Nadeau, P.H. & Hay, S., 2003, Model of shale permeability as a function of the temperature: Application to Mesozoic mudstones, Norwegian Continental Shelf. EAGE. Annual Meeting, Stavanger, Program Abstract C26.

Schmidt, V. and McDonald, D.A. 1979. The role of secondary porosity in the course of sandstone diagenesis. SEPM Special Publication 26, 157-207.

Surdam, R.C., Boeses, W. and Crossey, L.J. 1984. The chemistry of secondary porosity. In: Clastic Diagenesis, McDonald, D.A. and Surdam, R.C. (eds), AAPG Memoir 37, 127-150.

Steen, Ø. & Nadeau, P.H. 2007. A Global Overview of the Temperature Gradients in Continental Basins and Their Relationship with Tectonic Settings. AAPG Annual Meeting, Long Beach, AAPG Search and Discover Article #90063.

Tripsanas, E.K., Bryant, W.R. and Phaneuf, B. 2004a. Slope instability processes caused by salt movements in a complex deep-water environment, Bryant Canyon area, northwest Gulf of Mexico. AAPG Bulletin 88, 801-824.

Tripsanas, E.K., Bryant, W.R. and Phaneuf, B. 2004b. Depositional processes of uniform mud deposits (unifites), Hedberg Basin, northwest Gulf of Mexico: new perspectives. AAPG Bulletin 88, 825-840.

Vigorito, M. and Hurst, A. 2010. Regional sand injectite architecture as a record of pore pressure evolution and sand redistribution in the shallow crust: insights from the Panoche Giant Injection Complex, California. Journal Geological Society of London 167, 889-904.

Walderhaug, O. 1994. Precipitation rates for quartz cement in sandstones determined by fluid-inclusion microthermometry and temperature-history modeling. Journal of Sedimentary Petrology A64, 324-333.

Walderhaug, O. 1996. Kinetic modeling of quartz cementation and porosity loss in deeply buried sandstone reservoirs. AAPG Bulletin 80, 731-745.

Walderhaug, O., Lander, R.H., Bjørkum, P.A., Oelkers, E.H., Bjørlykke, K.,and Nadeau P.H. 2000. Modeling of quartz cementation and porosity in reservoir sandstones: Examples from the Norwegian Continental Shelf. In: R. Wordern (ed.) Quartz cementation: Int. Assoc. of Sediment. Spec. Publication 29, 39-49.

Walderhaug, O., Bjørkum, P.A., Nadeau, P.H. and Langnes, O. 2001. Quantitative modeling of basin subsidence caused by temperature-driven silica dissolution and reprecipitation. Petroleum Geoscience 7, 107-113.

Walderhaug, O., Oelkers, E.H. and Bjørkum, P.A. 2004. An analysis of the role of stress, temperature and pH in chemical compaction of sandstones: Discussion. Journal of Sedimentary Research 74, 447-449.

Waples, D.W. 1998. Basin modeling: how well have we done? In: Basin modeling: practice and progress, Duppenbecker, S.J. and Iliffe, J.E. (eds), Geological Society of London Special Publication 141, 1-14.

Waples, D.W. and Couples, G.D. 1998. In: Basin modeling: practice and progress, Duppenbecker, S.J. and Iliffe, J.E. (eds), Geological Society of London Special Publication 141, 73-81.

Weaver, C.E. 1960. Possible uses of clay minerals in the search for oil. AAPG Bulletin 44, 1505-1518.

BP Document Production:

1) Daily Geological Reports for Macondo -

October 31, 2009 (Bates BP-HZN-2179MDL00008541-42)

March 9, 2010 (Bates BP-HZN-2179MDL00058613-14)

March 17, 2010 (Bates BP-HZN-2179MDL00058365-66)

March 18, 2010 (Bates BP-HZN-2179MDL00058265-66)

March 19, 2010 (Bates BP-HZN-2179MDL00059220-22)

March 20, 2010 (Bates BP-HZN-2179MDL00058107-08)

March 21, 2010 (Bates BP-HZN-2179MDL00058333-34)

March 22, 2010 (Bates BP-HZN-2179MDL00058005-06)

March 23, 2010 (Bates BP-HZN-2179MDL00058604-05)

March 24, 2010 (Bates BP-HZN-2179MDL00059626-29)

March 26, 2010 (Bates BP-HZN-2179MDL00059209-10)

March 27, 2010 (Bates BP-HZN-2179MDL00059892-93)

March 28, 2010 (Bates BP-HZN-2179MDL00059710-11)

March 29, 2010 (Bates BP-HZN-2179MDL00058509-11)

March 30, 2010 (Bates BP-HZN-2179MDL00058251-53)

March 31, 2010 (Bates BP-HZN-2179MDL00059772-73)

April 1, 2010 (Bates BP-HZN-2179MDL00059483-84)

April 2, 2010 (Bates BP-HZN-2179MDL00059370-71)

April 3, 2010 (Bates BP-HZN-2179MDL00058504-06)

April 4, 2010 (Bates BP-HZN-2179MDL00058634-36)

April 5, 2010 (Bates BP-HZN-2179MDL00058326-28)

April 6, 2010 (Bates BP-HZN-2179MDL00058467-68)

April 7, 2010 (Bates BP-HZN-2179MDL00058918-19)

April 8, 2010 (Bates BP-HZN-2179MDL00058733-34)

April 9, 2010 (Bates BP-HZN-2179MDL00058539-40)

April 10, 2010 (Bates BP-HZN-2179MDL0009852-53)

April 11, 2010 (Bates BP-HZN-2179MDL00058665-66)

April 12, 2010 (Bates BP-HZN-2179MDL00058954-55)

April 13, 2010 (Bates BP-HZN-2179MDL00058450-51)

April 14, 2010 (Bates BP-HZN-2179MDL00058345-46)

April 15, 2010 (Bates BP-HZN-2179MDL00059185-86)

2) BP Technilogical Memorandum – Post Well Subsurface Description of Macondo Well (Bates BP-HZN-BLY001140873-910)

3) Shallow Hazards Assessment – MC 252#1 – June 8, 2009 (Bates BP-HZN-2179MDL02122363-408)

Add Energy Production:

4) Knudsen Email Discussing Macondo Temperatures (Bates AE-HZN-2179MDL00120407-14)

5) Macondo Temperature Curve (Bates AE-HZN-2179MDL00120415)

MDL 2179 Depositions:

6) Morten Haug Emilsen – Day One and Day Two (June 23 and 24, 2011)

FIGURES LIST

1. Location of the Macondo 252 #1 well, northern Gulf of Mexico along with the GoM reservoirs data base used by Ehrenberg et al. (2008a).

2. A depth (km) plot of subsurface pressure regimes (MPa) showing the divergence of the hydrostatic and lithostatic gradients with increased depth. An idealised pore-pressure history that is representative of a North Sea pressure profile (Buller at al. 2005) marks the onset of overpressure above 3 km forming a ramp that approaches lithostatic pressure. HPHT = high-temperature high-pressure and will be discussed later.

3. Temperature-dependent mineral assemblages in mudstones and sandstones. Solid lines represent the temperature range at which specific minerals are stable, dashed lines indicate a possible range of occurrence and **?** indicates uncertainty (modified from Hoffman and Hower, 1979). All the minerals shown are clay minerals except for 2M mica and K-feldspar. Since publication of this work substantial redefinition of the temperature stability ranges and nomenclature of the clay mineral stabilities has been made.

4. The three-fold temperature zonation of sedimentary basins: the expulsion zone – 120-200°C; the accumulation zone – 60-120°C; compaction zone - <60°C. The expulsion zone is synonymous with HPHT conditions and limited hydrocarbon reserve potential. The accumulation zone is also known as the Golden Zone (Buller at al. 2005) and is the optimum petroleum accumulation zone (after Nadeau 2011a).

5. A plot of temperature (°C) against the bulk oil to gas ratio from >10,000 US Gulf of Mexico reservoirs. Four main compositional types are identified: oil, wet gas, dry gas and gas condensate (GC); modified from Nadeau et al. (2005).

6. Idealised pore-pressure curves from three different sedimentary basins (A, B, C) plotted against depth (left) and temperature (right). Overpressure ramps (see Figure 2), green, red and blue are similar but occur at different depths. When plotted against temperature the pressure ramps coincide. Clearly depth (a proxy for mechanical compaction) has no relationship to pore pressure whereas temperature does (after Buller et al. 2005).

7. Merging of figures 4 and 6 illustrates the relationship between the GoM reservoirs data and the three-fold Golden Zone zonation.

8. An approximately north-south section through the offshore northern area of the GoM (Nadeau 2011a). A thick Paloegene and Neogene sedimentary fill is present in the north. Steep grey features (diapirs) are salt that has risen from the Jurassic into younger formations, deforming and segmenting them. Water depth increases to the south. The 60°C and 120°C isotherms cut strata of all ages and deepen southward (offshore) where geothermal gradients are lower. The top of the HPHT zone (the 120°C isotherm) is independent of depth or geological age.

9. Plot of reservoir temperature against reservoir pressure (specific gravity) for 11,864 reservoirs from the US GoM. The median P50 curve increases exponentially at >60°C and at 120°C P50 is >1.4 SG and enters the HPHT regime (the expulsion zone of Figure 4). Temperature v. pressure was chosen initially (Nadeau 2011a) rather than depth v. pressure because geothermal gradients in the GoM vary widely (14°C to 36°C, Ehrenberg 2008b).

The current industry definition of the HPHT regime is shown as is the geologically-defined HPHT regime. Less than 1% of reserves fall into the current industry defined HPHT regime (Nadeau 2011a).

Figure 10. a - Plot of burial rate (metres/million yrs) against reservoir pressure with the same data as in Figure 8; burial rate is a proxy for the rate of mechanical compaction. No obvious relationship is present. Burial rate is a proxy for lithostatic load that following deposition is the predominant driver of sediment compaction and porosity loss until 60°C is reached. a = data from all reservoirs; b = data from reservoirs from <60°C in which the only trend noted is along the P10 probability (after Nadeau 2011a).

11. A schematic depth v. pressure plot showing the hydrostatic gradient and the global leak-off pressure (LOP) trend. The 1.7 g/cm^3 pressure gradient is marked and represents the specific gravity reservoir pressure that is typical of many overpressured GoM reservoirs Nadeau 2011b).

12. The area of anomalously low LOP's from the Louisiana GoM offshore that are focused around the Mississippi Submarine Canyon (Nadeau 2011b). Low LOP's are indicative of strata with low confining stress and weak physical integrity. They are likely to damage easily when drilled.

13. A schematic leak-off pressure (LOP) test plotted against time. The test is performed by pumping drilling mud into a borehole at a constant rate. Typically LOP tests are stopped when mud starts to leak into the formation – hence leak-off pressure. If mud is pumped beyond the LOP the formation breakdown pressure (FBP) may be reached at which time hydraulic fracture of the formation occurs. FBP is typically ~10% greater than LOP. Following breakdown (hydraulic fracture) of the formation fractures will continue at the fracture propagation pressure (FPP), which is often very similar to the LOP (after Nadeau 2011b).

14. Location of earthquake epicentres local to the Mississippi Submarine Canyon. The area in which anomalously low leak-off pressures (LOP's) are recorded in offshore Louisiana that are located around the Mississippi Canyon.

15. a – Gravitationally-driven slumping characterises GoM seafloor instability in the area of the Mississippi Canyon. Series of retrogradational slumps collapse and redistribute sediment. The slumps are instantaneous events where in excess of 100 m thick and many km^2 area bodies of sediment are detached and move rapidly downslope. b - Pre-slump pressure conditions in the area from which sediment was removed. Formations **A** and **B** are in the Golden Zone with pore pressure close to the fracture gradient (equivalent to the formation breakage pressure). c - Post-slump pressure conditions in the area from which sediment was removed. Formations **A** and **B** have reached and crossed the fracture gradient, respectively because of the instantaneous unloading cased by slumping. Formation **B** will have undergone major hydraulic fracturing that caused shallow seismicity, and produced low confining-stress. Formation **A** will have incipient fracture development and weak physical character.

16. Oil seep distribution from the Gulf of Mexico (www.sarsea.org/natural_seepage.htm). Superimposed is the public-domain reservoir database used in figures 5, 8 and 9 from which their relationship to the Golden Zone is defined.

17. A synoptic that relates the instantaneous leftward/lower pore-pressure shift of the lithostatic gradient (see Figure 14) caused by decreasing the sediment load during large-scale slumping. The lower lithostatic gradient moves already overpressured formations over the fracture gradient thus initiating hydraulic fracture. In this figure a band of hydraulic fracture occurs slightly above the base of the Golden Zone at similar temperature to reservoirs in Macondo 252 #1.

18. High-pressure high-temperature (HPHT) definitions based on the stability limits of common well-service-tool components, elastomeric seals and electronic devices (DeBruijn et al. 2008). The limits are not directly related to geological criteria or data.

19. Geologically-defined HPHT conditions of T >120°C and reservoir pressure (SG) >1.4 g/cm^3 for GoM data (from Figure 8). Most HPHT reservoirs occur below the technology-defined P and T limits (green oval). Many severe overpressures (orange oval) occur at lower temperature than the technology-defined limits.

Curriculum Vitae

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d.o.b. 05.09.53

I am driven by my love of earth science and its importance in the future wealth and prosperity of society. My career has been driven by a fascination for the breadth of science that can be applied to geology. Consequently, my career has given me opportunities to collaborate with many excellent people from a range of disciplines who have provided me with immeasurable support, inspiration and friendship; I pay tribute to my collaborators.

Research

My research is broad-based, driven by an underlying interest in sedimentary materials, their transport, deposition and preservation, and their stability during the weathering-transport-diagenetic cycle, and recently focused on the quantification of the physical characteristics of sediments and sedimentary rocks. Observational science is the cornerstone of earth science and I am committed to maintaining and improving observational skills in earth science education. Observational science is a fundamental driver for all my research and I believe that it is critical to the continued health of the earth science community, vital to successful technological applications, and a strong facet of the outreach of earth science to laymen. In academia I strive to transmit my enthusiasm and experience to students and colleagues, I hope inspiring them to invest their future in the subject that I love.

Career details
Chronology

2008 – present	Advisor, exploHUB
2002	Founder of exploHUB (U Aberdeen Centre for Regional Exploration Training)
1997– present	Chair of Production Geoscience, U Aberdeen
1992–1997	Shell Chair of Production Geoscience, U Aberdeen
1992-1994	Director of the Production Geoscience Research Unit, U Aberdeen
1990-1992	Advising Geologist, Unocal UK
1986-1990	Staff Geologist, Statoil Norway
1983-1986	Senior Geologist, Statoil Norway
1981-1983	Geologist, Statoil Norway
1979	Research Fellow, University of Bergen
1977-1980	PhD Sedimentology Research Laboratory, University of Reading
1973-1977	BSc Geology & Mineralogy, University of Aberdeen

Awards

William Smith Award 1993 (Geological Society of London)

Wegener Medal 2004 (European Association of Geoscientists & Engineers)

Distinguished Service Award 2007 (American Association of Petroleum Geologists)

Educational experience

Teaching

Prior to my academic career I was involved in post-graduate level teaching in Norwegian universities (Trondheim, Rogaland). In Statoil I was given responsibility for developing cross-disciplinary field training courses and providing courses in geology for petroleum engineers.

2005 Course Director, MSc Integrated Petroleum Geoscience

1998 - MSc Projects Coordiniator

University of Aberdeen

2010 - BSc 4th level Field Geology – volcanic margins

2004 - MSc Basin modelling

2003 - BSc 4th level Petroleum Systems

2002 BSc 4th level Sedimentology

2001 - BSc 1st level Field geology

1999 - 2004 BSc 4th level Advanced analysis of sedimentary rocks

1997 - 2000 BSc 2nd level Field Geology

1996 - BSc 1st level Sedimentology

1992 - MSc Prospect evaluation & risk (Exploration and petroleum basin evaluation)

1992 -1996 MSc Production geoscience

University of Trondheim

1985 to 1990 - MSc level Reservoir characterisation

University of Rogaland

1988 - MSc level Reservoir characterisation

Statoil

1985 to 1987 - Geology for petroleum engineers

1984 to 1990 - Geological reservoir characterisation, field teaching

Extra-mural

I am committed to Continued Professional Development and have a regular involvement in a variety of programmes teaching petroleum geosciences to Lawyers, engineers and economists.

I run courses in geoscience for non-professionals.

2002 to present day – co leader of 12 *Sand Injectite* field courses for oil industry clients (~150 participants)

1996 - 2001 – co leader (with B.T. Cronin) of 17 *Reservoir characterisation of sand-rich turbidite reservoirs* for oil industry personnel

Research supervision
University of Aberdeen
Supervision of 16 PhD (13 completed) and 65 MSc projects (1992-2011)
Universities Oslo, Trondheim and Bergen
Supervision of 6 research MSc's (1984 – 1990)

University service

2008-	Advisor to exploHUB
2005	Director, MSc Petroleum Geoscience
2002	Founder exploHUB
2001	Chairman/Founder of AUVIS (3-D visualisation programme)
2000-	Director, Sand Injection Research Group
1999	Co-ordinator/Leader of the UA Petroleum Research Centre initiative
1998	Founder of the Aberdeen Geological Alumnus (AGA)
1997-2001	Chairman, Departmental Research Committee,
1996-2001	Managed/co-managed Turbidite Research Group
1996-1999	Founder/Chair of the UA Uncertainty network,
1996-99	Chairman of the Industry-Academia Forum
1995-96	Departmental Contact for Student Disabilities
1994-98	UBD MSc Petroleum Geoscience external examiner
1992-96	Secretary, Petroleum Geoscience Research Advisory Board

Extra mural service

2010	DEVEX Committee Member
2009-	Co Founder of *Fabric of the Land* art exhibition in U Aberdeen Dept Geology & Petroleum Geology – artistic inspiration from the fabric of planet earth: a fusion of geology and art in a working geology department
2008-	External Examiner MSc Petroleum Geoscience, U Brunei
2008-	AAPG 100th Anniversary Committee Coordinator/Chief Editor of Outcrop Guide (Outcrops that have changed the way we practice petroleum geology)
2007	FORCE Invited keynote speaker "Stratigraphic Traps associated with Sand Injectites" (Stavanger)
2007-	AAPG 100th Anniversary Committee

2007-	EAGE Distinguished Lecturer (Large-scale sandstone injection complexes – new targets for exploration drilling) – with Peter B Rawlinson and Wytze de Boer (Marathon Oil Europe)
2005-.	Norwegian Research Council Evaluation Committee PETROMAX
2005-08	Vice-Chairman AAPG Publication Committee
2004	FORCE Invited keynote speaker on Sand Injectites (Stavanger)
2003	Harnessing Computer Technology to Deliver Better E&P Returns, Chairman, Energy Institute & Hewlett Packard
2003-2006	EAGE Distinguished Lecturer (Sand Injectites)
2002-2005	Elected European Representative on AAPG Advisory Council
2002-2005	Elected as a Trustee and Council Member of the Geological Society of London
2001-2003	Technical Committee, 6th NW Europe Hydrocarbons Conference, (Chair, Deep-water clastics)
2001	UK Government (NERC) ROPA committee
2001	International Panel (+Marge Wilson & Sierd Cloetingh) to the Norwegian Geological Society, "The Future of Earth Science in Norway"
2000-02	Technical Programme Officer (Petroleum) for EAGE
2000	Co-Chairman of the SPWLA Annual Research Conference, Taos, USA
1999	Co-Chairman on the Research Appraisal Panel for the Petroleum Division of GEUS (Denmark/Greenland Geological Survey)
1999	Member of the UK Government Innovation & Technology workgroup of the Oil & Gas Industry Task Force
1999-2000	Organising Committee for the EAGE Annual Conference, Glasgow 2000
1997	Technical Committee, 5th NW Europe Hydrocarbons Conference
1997-2002	EAGE Annual Conference Technical Programme Committee (Chair, Reservoir Geology section)
1996-2000	Member of the EAGE Reservoir Management Committee,
1996	Technical Committee, PETEX
1994-2000	Chief (Founding) Editor of Petroleum Geoscience
1994-2000	Member of the Geological Society Publications Committee
1992-94	Advisor to the Minister of Education, Brunei (MSc Petroleum Geoscience)
1992-2001	Editorial Advisor First Break
1990-1998	Executive Editor Sedimentary Geology,

1990- UK Government (NERC, ESPRC) research assessor

Geo'Outreach

2010 ongoing U Ghana at Accra – Initiative in Petroleum Geoscience education and research

2009 BSc National Mapping School with the Nigerian Petroleum Technology Development Fund

1993-94 Co-designed and founded the Dept. Petroleum Geoscience at U Brunei, assisted in hire of staff and defining curriculum

Membership of Professional Societies
Geological Society of London (C.Geol. FGS), International Association of Sedimentologists, American Association of Petroleum Geologists, European Association of Geoscientists & Engineers, Society of Petroleum Engineers, Society of Professional Well Log Analysts, Petroleum Exploration Society of Great Britain

Publications

157. HURST, A., SCOTT, A. and VIGORITO, M. 2011. Physical characteristics of sand injectites, Earth-Science. Reviews 106, 215-246.

156. VIGORITO, M. and HURST, A. 2010. Regional sand injectite architecture as a record of pore pressure evolution and sand redistribution in the shallow crust: insights from the Panoche Giant Injection Complex, California. Journal Geological Society of London 167, 889-904.

155. SZARAWARSKA, E., HUUSE, M., HURST, A., DE BOER, W., LU, L., MOLYNEUX, S. & RAWLINSON, P. 2010. 3D seismic characterization of large-scale sandstone intrusions in the lower Paleogene of the North Sea: completely injected vs. in situ remobilized saucer-shaped sand bodies. Basin Studies

154. HUUSE, M., JACKSON, C. . CARTWRIGHT, J.A. and HURST, A. 2009. Large-Scale Sand Injectites in the North Sea: Seismic and Event Stratigraphy and Implications for Hydrocarbon Exploration. AAPG Search and Discovery Article #40481.

153. SCOTT, A., VIGORITO, M. and HURST, A. 2009. The process of sand injection: internal structures and relationships with host strata (Yellowbank Creek injectite complex, California). Journal of Sedimentary Research 79, 568-583.

152. HURST, A. 2009. Bathonian to Oxfordian strata of the Brora area. Excursion 2 in: Excursion guide to the Geology of East Sutherland and Caithness, 2nd edition, (N.H. Trewin & A. Hurst eds.), Dunedin Academic Press, Edinburgh, p. 48-73.

151. TREWIN, N.H. and HURST, A. 2009. Excursion guide to the Geology of East Sutherland and Caithness, 2nd Edition, Trewin, N.H. & Hurst, A. (eds), Dunedin Academic Press, Edinburgh, 183 p.

150. HURST, A., TISCHLER, G. and RAVI, A. 2009. Predicting reservoir characteristics from drilling and hydrocarbon-gas data using advanced computational mathematics. SPE 123785. Offshore Europe, September 2009, Aberdeen.

149. HURST, A. 2009. Bathonian to Oxfordian strata of the Brora area. In: Geology of East Sutherland and Caithness (N.H. Trewin & A. Hurst eds.), Geological Society of Aberdeen,

148. BRACCINI,E., DE BOER, W., HURST, A., HUUSE, M., VIGORITTO, M., and TEMPLETON, G. 2008. Sand injectites. Oilfield Review 20, 34-49.

147. CARTWRIGHT, J.A., JAMES, D., HUUSE, M, VETEL, W. and HURST, A. 2008. The geometry and emplacement of conical sandstone intrusions. Journal of Structural Geology 30, 854-867.

146. VIGORITO, M., HURST, A., CARTWRIGHT, J.A., & SCOTT, A. 2008. Architecture of a sand injectite complex: implications for origin and timing. Journal of the Geological Society of London 165, 609-612.

145. CRONIN, B.T., ÇELIK, H., & HURST, A. 2007. Sinuous channels in late stages of entrenched deep-water channel complexes, Hasret Mountain Main Channel, Turkey. Paper 92, In: Atlas of deep-water outcrops, Nilsen, T.H., Shaw, R.D., Steffans, G.S. and Studlick, J.R.J. AAPG Studies in Geology 56, CD-Rom, 368-372.

144. CRONIN, B.T., ÇELIK, H., HURST, A., GUL, M., GURBUZ, K., MAZZINI, A. & OVERSTOLZ, M. 2007. Slope-channel complex fill and overbank architecture, Tinker Channel, Kirkgecit Formation, Turkey. Paper 91, In: Atlas of deep-water outcrops, Nilsen, T.H., Shaw, R.D., Steffans, G.S. and Studlick, J.R.J. AAPG Studies in Geology 56, CD-Rom, 363-367.

143. CRONIN, B.T., GURBUZ, K., GUL, M., ÇELIK, H., HURST, A. & KELLING, G. 2007. Evolution of multi-phase, winged, coarse-grained deep-water canyons: Alikayasi Canyon, Turkey. Paper 90, In: Atlas of deep-water outcrops, Nilsen, T.H., Shaw, R.D., Steffans, G.S. and Studlick, J.R.J. AAPG Studies in Geology 56, CD-Rom, 357-362.

142. SATUR, N., HURST, A. KELLING, K., CRONIN, B.T. and GURBUZ, K. 2007. Controlling Factors on the Characteristics of Feeder Systems to a Deep-marine Fan, Cingoz Formation, Turkey. Paper 89, In: Atlas of deep-water outcrops, Nilsen, T.H., Shaw, R.D., Steffans, G.S. and Studlick, J.R.J. AAPG Studies in Geology 56, CD-Rom, 351-356.

141. HURST, A., DURANTI, D.,HUUSE, M. & CARTWRIGHT, J.A. 2007. Sand injectites in outcrops of deep-water clastics. Paper 9, In: Atlas of deep-water outcrops, Nilsen, T.H., Shaw, R.D., Steffans, G.S. and Studlick, J.R.J. AAPG Studies in Geology 56, CD-Rom, 30-35.

140. SATUR, N., HURST, A., KELLING, G., CRONIN, B.T. & GURBUZ, K. 2007. Controlling factors on the character of feeder systems to a deep-marine fan, Cingoz Formation, Turkey. Paper 148, In: Atlas of deep-water outcrops, Nilsen, T.H., Shaw, R.D., Steffans, G.S. and Studlick, J.R.J. AAPG Studies in Geology 56, CD-Rom, 28p..

139. HURST, A., HUUSE, M., CARTWRIGHT, J.A., & DURANTI, D. 2007. Sand injectites in deep-water clastic reservoirs: are they there and do they matter? Paper 120, In: Atlas of deep-water outcrops, Nilsen, T.H., Shaw, R.D., Steffans, G.S. and Studlick, J.R.J. AAPG Studies in Geology 56, CD-Rom, 24p.

138. JONK, R., DURANTI, D., HURST, A.., PARNELL, J. & FALLICK, A.E. Aqueous and petroleum fluid flow associated with injected sandstones: an example from the Dinantian Oil-Shale Group of the Midland Valley, Scotland. In: Sand Injectites: Implications for hydrocarbon exploration and production, Hurst, A. & Cartwright, J. (eds.), AAPG Memoir 87, Tulsa, p.265-274.

137. GLENNIE, K. & HURST, A. 2007. Fluidisation and associated soft-sediment deformation in aeolian sandstones: Hopeman Sandstone (Permian), Scotland, and Rotliegend, North Sea. In: Sand Injectites: Implications for hydrocarbon exploration and production, Hurst, A. & Cartwright, J. (eds.), AAPG Memoir 87, Tulsa, p.221-226.

136. JONK, R., CRONIN, B.T. & HURST, A. Sand extrusion at the sediment-water interface: sand volcanoes from the Namurian of County Clare, Ireland. In: Sand Injectites: Implications for hydrocarbon exploration and production, Hurst, A. & Cartwright, J. (eds.), AAPG Memoir 87, Tulsa, p.221-226.

135. SATUR, N. & HURST, A. 2007. Sand fluidisation structures from the Ty Formation (Paleocene), Sleipner Øst field, Norwegian North Sea. In: Sand Injectites: Implications for hydrocarbon exploration and production, Hurst, A. & Cartwright, J. (eds.), AAPG Memoir 87, Tulsa, p.113-117.

134. DE BOER, W., RAWLINSON, P.B. & HURST, A. 2007. Successful exploration of a sand injectite complex: Hamsun prospect, Norway Block 24/9. In: Sand Injectites: Implications for hydrocarbon exploration and production, Hurst, A. & Cartwright, J. (eds.), AAPG Memoir 87, Tulsa, p.65-68.

133. HUUSE, M., CARTWRIGHT, J.A., DURANTI, D., HURST, A. & STEINSLAND, N. 2007. Seismic characterization of large-scale sandstone intrusions. In: Sand Injectites: Implications for hydrocarbon exploration and production, Hurst, A. & Cartwright, J. (eds.), AAPG Memoir 87, Tulsa, p.21-35.

132. HURST, A. & CARTWRIGHT, J.A. 2007. Relevance of sand injectites to hydrocarbon exploration and production. In: Sand Injectites: Implications for hydrocarbon exploration and production, Hurst, A. & Cartwright, J. (eds.), AAPG Memoir 87, Tulsa, p.1-19. ISBN: 978-0-89181-368-2.

131. SCHWAB, A.M., TREMBLAY, S. & HURST, A. 2007. Seismic expression of turbidity-current and bottom-current processes on the northern Mauritanian continental slope. In: Seismic Geomorphology: Applications in Hydrocarbon Exploration and Production, Davies, R.J., Posamentier, H.W., Wood, L.J. & Cartwright, J.A. (eds.), Geological Society of London Special Publication 277, 237-252.

130. HURST, A., CARTWRIGHT, J.A., HUUSE, M. & DURANTI, D. 2006. Extrusive sandstones (extrudites): a new class of stratigraphic trap? In: in, M.R. Allen, G.P. Goffey, R.K. Morgan and I.M. Walker eds., The deliberate search for stratigraphic traps: where are they now? Geological Society (London) Special Publication 254, p. 289-300.

129. DeMIS, W.D., HARTMANN, D. & HURST, A. 2006. By-passed pays and plays. Short Course #4, AAPG Annual Convention, Houston.

128. CARTWRIGHT, J.A. & HURST, A. 2005. Characterisation of remobilised deepwater sandstone reservoirs. Oil & Gas – Maximising Recovery Programme IOR Views (http://ior.rml.co.uk/issue11/research-development/universities/aberdeen/), DTI Licensing and Consents Unit.

127. JONK, R., PARNELL, J. & HURST, A. 2005. Aqueous and petroleum fluid flow associated with sand injectites. Basin Research 17, 241-257.

126. RAWLINSON, P., De BOER, W. & HURST, A. 2005. Successful exploration of a sand injectite complex: Hamsun prospect, Block 24/9, Norwegian North Sea. 67th EAGE Conference & Technical Exhibition, Madrid. Paper A-02.

125. HUUSE, M., CARTWRIGHT, J., GRAS, R. & HURST, A. 2005. Giant conical sandstone intrusions in the lower Eocene of the Outer Moray Firth (UK North Sea): migration paths and potential reservoirs. In: Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference, Dore, A. & Vining, B. (eds), Geological Society, London, p.1577-1594.

124. HURST, A., FRASER, A., FRASER, S. & HADLER-JACOBSEN, F. 2005. Deep-water clastic reservoirs: a leading global play in terms of reserve replacement and technological challenges. In: Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference, Dore, A. & Vining, B. (eds), Geological Society, London, p.1111-1120.

123. HURST, A., CARTWRIGHT, J.A., DURANTI, D., HUUSE, M. & NELSON, M. 2005. Sand injectites: an emerging global play in deep-water clastic environments In: Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference, Dore, A. & Vining, B. (eds), Geological Society, London, p.133-144.

122. JONK, R., HURST, A., DURANTI, D., MAZZINI, A., FALLICK, A.E. & PARNELL, J. 2005. The origin and timing of sand injection, petroleum migration and diagenesis: the Tertiary petroleum system of the South Viking Graben, North Sea. AAPG Bulletin 89, 329-357.

121. SATUR, N., KELLING, G., CRONIN, B.T., HURST, A. & GURBUZ, K. 2005. Sedimentary architecture of a canyon-style fairway feeding a deep-water clastic system, the Miocene Cingoz Formation, southern Turkey: significance for reservoir characterisation and modelling. Sedimentary Geology 173, 91-119.

120. HURST, A., CARTWRIGHT, J.A., HUUSE, M. & DURANTI, D. 2005. Sand injectites – an ignored global exploration opportunity. Offshore Magazine

119. HUUSE, M., DURANTI, D. STEINSLAND, N., GUARGENA, C., PRAT, P., HOLM, K. CARTWRIGHT, J.A. & HURST, A. 2004. Seismic characteristics of large-scale sandstone intrusions in the Paleogene of the South Viking Graben, UK and Norwegian North Sea. *In*: 3-D Seismic Technology: Applications to the Exploration of Sedimentary Basins (Davies, R.J., Cartwright, J.A., Stewart, S.A., Lappin, M. & Underhill, J.R. eds.). Geological Society of London Memoirs, 29, 263-277.

118. HURST, A., DURANTI, D., HUUSE. M. & CARTWRIGHT, J.A. 2004. Sand injectites in deep-water clastic plays: migration paths, intrusive traps and reservoir characterization. 66th EAGE Conference & Technical Exhibition, Paris. Paper A025.

117. HURST, A., KOVALCHUK, A., GRANDJEAN, V., PLAYER, M. & WATSON, J. 2004. Non-destructive characterization of reservoir grain and pore size by optical imaging. 66th EAGE Conference & Technical Exhibition, Paris. Paper D022.

116. DURANTI, D. and HURST, A. 2004. Fluidisation and injection in the deep-water sandstones of the Eocene Alba Formation (UK North Sea). Sedimentology 51, 503-531.

115. SATUR, N., CRONIN, B.T., HURST, A., KELLING, G. & GURBUZ, K. 2004. Down-channel variations in stratal patterns within a conglomeratic, deepwater fan feeder system (Miocene, Adana Basin, Southern Turkey. In: Confined Turbidite Systems (Lomas, S.A. & Joseph, P. eds.) Special Publication of the Geological Society of London, 222, 241-260.

114. MAZZINI, A., DURANTI, D., JONK, R., PARNELL, J., CRONIN, B.T., HURST, A. and QUINE, M. 2003. Palaeo-carbonate seep structures above an oil reservoir, Gryphon Field, Tertiary, North Sea. Geo Marine Letters 23, 323-339. ISSN: 0276-0460.

113. KOVALCHUK, A.,GRANDJEAN, V.,HURST, A., PLAYER, M.A., & WATSON, J. 2003. Characterisation of the physical properties of porous media using monochrome imaging. Proc. SPIE (Society of Photo-Optical Instrumentation Engineers), v. 5477, 138-150.

112. HURST, A., CARTWRIGHT, J.A., HUUSE, M., JONK, R., SCHWAB, A.M., DURANTI, D. & CRONIN, B.T. 2003. Significance of large-scale sand injectites as long-term fluid conduits: evidence from seismic data. Geofluids 3, 263-274.

111. HUUSE, M., DURANTI, D. GROVES, S., GUARGENA, C., PRAT, P., HOLM, K. STEINSLAND, N., CRONIN, B.T., HURST, A. & CARTWRIGHT, J.A. 2003. Sandstone intrusions: detection and significance for exploration and production. First Break 21, 33-42.

110. JONK, R., DURANTI, D., PARNELL, J., HURST, A. & FALLICK, A.E. 2003. The structural and diagenetic evolution of injected sandstones: examples from the Kimmeridgian of NE Scotland. Journal of the Geological Society of London 160, 881-894.

109. HURST, A. CARTWRIGHT, J.A. and DURANTI, D. 2003. Fluidisation structures in sandstone produced by upward injection through a sealing lithology. In: Subsurface sediment mobilization (van Rensbergen, P., Hillis, R.R., Maltman, A.J. & Morley, C.K. eds.). Geological Society, London, Special Publications, 216, 123-137.

108. JONK, R., MAZZINI, A., DURANTI, D., PARNELL, J., CRONIN, B. & HURST. A. 2003. Fluid escape from reservoirs: implications from cold seeps, fractures and injected sands Part II. The fluids involved. Journal of Geochemical Exploration 78-79, 297-300.

107. MAZZINI, A., JONK, R., DURANTI, D., PARNELL, J., CRONIN, B. & HURST. A. 2003. Fluid escape from reservoirs: implications from cold seeps, fractures and injected sands Part I. The fluid flow system. Journal of Geochemical Exploration 78-79, 293-296.

106. HURST, A. (ed.) 2002. Onshore-Offshore relationships on the North Atlantic margin. Abstracts and Proceedings of the Norwegian Geological Society, NGF 2, 211p.

105. OGILVIE, S.R., CUDDY, S., LINDSAY, C. and HURST, A. 2002. Novel methods of permeability prediction from NMR tool data. Dialog 10.

104. HUUSE, M., DURANTI, D. PRAT, P., HOLM, K. STEINSLAND, N., GUARGENA, C., CARTWRIGHT, J.A. HURST, A. and CRONIN, B.T. 2002. Detection, origin and significance of large-scale injected sand bodies in the North Sea Cenozoic. 64th EAGE Conference & Technical Exhibition, Florence. Paper H-19.

104. CRONIN, B.T., SPADINI, G., ROCCHINI, P. and HURST, A. 2002. Merging high-resolution, modern deep-water data sets with West Africa subsurface data to validate sand body geometry and reservoir facies distribution. 64th EAGE Conference & Technical Exhibition, Florence. Paper P056

103. JONK, R., HURST, A. and PARNELL, J. 2002. Fluid flow through sand injectites intruded in low permeability host rocks. 64th EAGE Conference & Technical Exhibition, Florence. Paper H-23.

102. HURST, A., CARTWRIGHT, J.A., DURANTI, D, HUUSE, M., and CRONIN, B.T. 2002. Sand injectites – reserve potential, their genesis and reservoir character. 64th EAGE Conference & Technical Exhibition, Florence. Paper G-32.

101. DURANTI, D., HUUSE, M., CARTWRIGHT, J.A. HURST, A., CRONIN, B.T., MAZZINI, A. and FLANAGAN, K. 2002. Unusual facies and geometries of the Paleogene deep-water systems in the North Sea – effects of sand remobilisation. 64th EAGE Conference & Technical Exhibition, Florence. Paper .

100. DURANTI, D., HURST, A., BELL, C. and GROVES, S. 2002. Injected and remobilised sands of the Alba Field (UKCS): sedimentary facies characteristics and wireline log responses. Petroleum Geoscience 8, 99-107.

99. ROBERTSON, E., CORBETT, P., HURST, A., SATUR, N. and CRONIN, B.T. 2002. Synthetic well test modelling in a high net-to-gross outcrop system for turbidite reservoir description. Petroleum Geoscience 8, 19-30.

98. HINEY, R. and HURST, A. 2001. Sub-seismic scale heterogeneity in sand-rich submarine fans – application of the "multi-system" approach within the Greater Brae area (UKCS). 63rd EAGE Conference & Technical Exhibition, Amsterdam. Paper L-06.

97. HUUSE, M., DURANTI, D., CARTWRIGHT, J., HURST, A.. and CRONIN, B. 2001. Seismic expression of large-scale sand remobilisation and injection in Paleogene reservoirs of the North Sea Basin and beyond. 63rd EAGE Conference & Technical Exhibition, Amsterdam. Paper L-07.

96. JONK, R., DURANTI, D., HURST, A. and PARNELL, J. 2001. Using image analysis to quantify textural changes due to post-depositional remobilization of fine-grained sands. 63rd EAGE Conference & Technical Exhibition, Amsterdam. Paper P583.

95. DUBRULE, O., DAMSLETH, E. and HURST, A. (eds.) 2001. Petroleum Geoscience, Special Issue – Thematic set on Geostatistics. Petroleum Geoscience 7, S1-107.

94. HURST, A. and MORTON, A.C. 2001. Generic relationships in the mineral-chemical stratigraphy of turbidite sandstones. Journal of Geological Society of London 158,401-404.

93. HURST, A. and CRONIN, B.T. 2001. The origin of consolidation laminae and dish structures in some deep-water sandstones. Journal of Sedimentary Research 71, 136-143.

92. HURST, A., BROWN, G.C. and SWANSON, R.I. 2000. Swanson's 30-40-30 rule. AAPG Bulletin 84, 1883-1891.

91. LOMAS, S.A., CRONIN, B.T., HARTLEY, A.J., DURANTI, D., HURST, A., MACKAY, E., CLARK, S.J., PALUMBO, B. and KELLY, S. 2000. Characterisation of lateral heterogeneities in an exceptionally exposed turbidite sand-body, Grès d'Annot (Eocene-Oligocene), SE France. In: Deep-water reservoirs of the world (eds. Weimer, P. *et al*., SEPM (GCS) Special Publication, p.502-513.

90. CRONIN, B.T., HURST, A., AKHMANOV, G., SPADINI, G. and ROCCHINI, P. 2000. Predicting deepwater turbidite reservoir quality and geometry. Offshore (November), pp. 98, 100, 141.

89. GARRETT, S.W., ATHERTON, T. and HURST, A. 2000. Lower Cretaceous deep-water sandstone reservoirs of the UK Central North Sea. Petroleum Geoscience 6, 231-240.

88. CRONIN, B.T., HARTLEY, A.J., CELIK, H., HURST, A. and TURKMEN, I. 2000. Equilibrium profile development in graded deep-water slopes: Eocene, Eastern Turkey. Journal Geological Society of London 157, 943-955.

87. CRONIN, B.T., GURBUZ, K. HURST, A. and SATUR, N. 2000. Vertical and lateral organisation of a carbonate deep-water slope marginal part of a submarine fan system, Miocene, southern Turkey. Sedimentology 47, 801-824.

86. ROBERTSON, E., CORBETT, P. AND HURST, A. 2000. Synthetic well test modelling in a high net to gross outcrop system for turbidite reservoir description. 62nd EAGE Conference & Technical Exhibition, Glasgow. Paper A18.

85. DURANTI, D., HURST, A., HANSON, R., BELL, C. and MACLEOD, M. 2000. Reservoir characterisation of a remobilised sand-rich turbidite reservoir: the Alba Field**.** 62nd EAGE Conference & Technical Exhibition, Glasgow. Paper X5.

84. HURST, A., CRONIN, B.T. and BALL, C. 2000. Seismic sedimentology of a submarine channel system. 62nd EAGE Conference & Technical Exhibition, Glasgow. Paper X7.

83. CRONIN, B.T. and HURST, A. 2000. Sandstone sheets associated with deep-water channels: subtle stratigraphic traps. 62nd EAGE Conference & Technical Exhibition, Glasgow. Paper X13.

82. CRONIN, B.T., HURST, A., CELIK, H. and TURKMEN, I. 2000. Superb exposure of a channel, levee and overbank complex in an ancient deep-water slope environment. Sedimentary Geology 132, 205-216.

81. HURST, A., CRONIN, B.T. and HARTLEY, A.J. 2000. The necessity of down-scaling when reservoir modelling sand-rich deep-water clastics. Petroleum Geoscience 6, 67-76.

80. SATUR, N., HURST, A., CRONIN, B.T., KELLING, G. and GURBUZ, K. 1999. Sand body geometry in a sand-rich, deep-water clastic system, Miocene Cingoz Formation of southern Turkey. Marine and Petroleum Geology 17, 239-252.

79. BURWOOD, R., GABRIELSEN, R.H. and HURST, A. 1999. Evaluation of oil- and gas-related research at the Geological Survey of Denmark and Greenland (GEUS). Danmarks og Grønlands Geologiske Undersøgelse Rapport 1999/69, 19p.

78. HURST, A. 1999. Reservoir studies – Introduction and review. *In:* Fleet, A.J. and Boldy, S.A.R. (eds.) Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, p.1175.

77. ASHCROFT, W.A., HURST, A. and MORGAN, C.J. 1999 Reconciling gravity and seismic data in the Faeroe-Shetland Basin, west of Shetland. *In:* Fleet, A.J. and Boldy, S.A.R. (eds.) Petroleum Geology ofNorthwest Europe: Proceedings of the 5th Conference, 595-600.

76. HURST, A., VERSTRALEN, I., CRONIN, B.T. and HARTLEY, A.J. 1999. Sand-rich fairways in deep-water clastic reservoirs: genetic units, capturing uncertainty and a new approach to reservoir modelling. AAPG Bulletin 83, 1096-1118.

75. HURST, A. 1999. Textural and geochemical micro-analysis in the interpretation of clay mineral characteristics: lessons from sandstone hydrocarbon reservoirs. Clay Minerals 34, 137-150.

74. HURST, A., LOMAS, S. and CRONIN, B. 1999. Architectural element analysis in sand-rich deep-water clastic reservoirs. 61st EAGE Conference & Technical Exhibition, 7-11 June, Helsinki. Paper 5-50, 4p.

73. HURST, A. and COLTER, V.S. 1998. A note on the exploration for the Wytch Farm oilfield, UK. Petroleum Geoscience 4, 377-379.

72. HURST, A.. HOLE, M.J., MORTON. A.C., HARTLEY, A.J. and PRESTON, D.J. 1998. Mineral-chemical stratigraphy in sandstone reservoir correlation. EAGE 60th Conference & Technical Exhibition, Leipzig, 4-40.

71. MILODOWSKI, A.E., HURST, A., WETTON, P.D., PEARCE, J.M., O'KNOX, R.W., HYSLOP, E.K. and EVANS, E. 1998. Petrophysical and petrographical Shearwater study phase II: evaluation of the mineralogical distribution of U, Th and K, and the relationship between wireline logs and petrophysical properties in Jurassic rocks (Fulmar and Pentland formations), wells 22/30b-11 amd 22/30b-15, Central Graben, North Sea. British Geological Survey, Technical Report WG/98/21C.

70. SKOPEC, R.A. and HURST, A. 1998. Permeameter, In: Instruments of Science, Bird, R. & Warner, D.J. (eds.). The Science Museum, London & The National Museum of American History, Smithsonian Institution, Garland Publishing Inc., New York & London, pp.447-449.

69. HURST, A. and MILODOWSKI, T. 1998. Natural gamma radiation in sandstone: causes and caution. Dialog 6, 6-8.

68. FOLEY, L., BALL, L., HURST, A., DAVIS, J. and BLOCKLEY, D. 1997. Fuzziness, incompleteness and randomness: Classification of uncertainty in reservoir appraisal. Petroleum Geoscience 3, 203-209. ISSN 1354-0793/97.

67. PROSSER, D.J., HURST, A. and WILSON, M.R. 1997. One man-operable probe permeameters. In: Advances in Petrophysics (M.A. Lovell & P. Harvey eds.), Geological Society Special Publication No. 122, p.11-18.

66. GLENNIE, K.W. and HURST, A. 1996. Hydrocarbon exploration and production in NW Europe: an overview of some key factors, In: AD1995 NW Europe's Hydrocarbon Industry (K.W. Glennie & A. Hurst eds.), Geological Society, 7-16.

65. GLENNIE, K.W. and HURST, A. 1996. AD1995 NW Europe's Hydrocarbon Industry. Geological Society of London, p. 242.

64. HURST, A. and MILODOWSKI, A. 1996. Thorium distribution on some North Sea sandstones: implications for petrophysical evaluation. Petroleum Geoscience 2, 59-68.

63. HURST, A., JOHNSON, H.D., et al. (1996) Geology of the Humber Group. Geological Society Special Publication No. 114, p.

62. FREER, G., HURST, A. and MIDDLETON, P. 1996. Upper Jurassic sandstone reservoir quality and distribution on the Fladen Ground Spur, In: Geology of the Humber Group (A.Hurst, H.D.Johnson *et al.* eds.), Geological Society Special Publication No. 114, 235-249.

61. SHIRODKAR, A., KIMMINAU, S., HURST, A. and MILODOWSKI, A. E. 1996. Origins of natural radioactivity in Fulmar sandstone from the North Sea Central Graben. E015.

60. HURST, A., MILODOWSKI, T. and SHIRODKAR, A. 1996. Sedimentological controls on reservoir quality in Fulmar formation sandstone in the central North Sea HPHT province, UKCS. EAGE. L018.

59. VERSTRALEN, I., HURST, A. and HARTLEY, A. 1996. Some origins of uncertainty in inter-well correlation of massive deep-water clastic sandstone reservoirs. EAGE. L017.

58. WARDELL, J.R., HAYES, M.R., BURFORD, S.J., McGUCKIN, J.J. and HURST. A. 1996. A 3-D geostatistical model of a turbidite reservoir and validation by pressure transient analysis. Society of Petroleum Engineers, 407-418. SPE 35538.

57. PROSSER, D.J., McKEEVER, M.E., HOGG, A.J.C. and HURST, A. 1995. Permeability heterogeneity within massive Jurassic submarine fan sandstones from the Miller Field, northern North Sea, UK. Geological Society Special Publication No. 94, 201-219.

56. VERSTRALEN, I., HARTLEY, A. and HURST, A. 1995. The sedimentological record of a late Jurassic transgression: Rona Member (Kimmeridge clay formation equivalent), West Shetland Basin, UKCS. Geological Society Special Publication No. 94, 155-176.

55. HURST, A., HALVORSEN, C. and SIRING, E. 1995. A rationale for routine laboratory probe permeametry. The Log Analyst , 10-20.

54. HURST, A. and NADEAU, P. 1995. Clay microporosity in reservoir sandstones: An application of quantative electron microscopy in petrophysical evaluation. AAPG Bulletin 79, 563-573.

53. MORTON, A. and HURST, A. 1995. Correlation of sandstones using heavy minerals: an example from the Statfjord Formation of the Snorre Field, northern North Sea. Geological Society Special Publication No. 89, 3-22.

52. VAGLE, G.B., HURST, A., DYPVIK, H. 1995. Origin of quartz cements from the Jurassic of the Inner Moray Firth (UK), Discussion. Sedimentology 42, 375-378.

51. HURST, A. 1995. Probe permeametry: Re-emergence of an old technology. First Break 13, No. 5.

50. HURST, A. and GOGGIN, D. 1995. Probe permeametry: An overview and bibliography. AAPG Bulletin 79, 463-473.

49. HURST, A. and NADEAU, P.H. 1994. Estimation of water saturation from clay microporosity data. SPE 28850.

48. HURST, A. and MILODOWSKI, A. 1994. Characterisastion of clays in sandstones: Thorium content and spectral log data. SPWLA Transactions of 16th European Formation Evaluation Symposium, Paper S.

47. HURST, A. and NADEAU, P.H. 1994. A little clay - volumes of problems. SPWLA Transactions of 16th European Formation Evaluation Symposium, Paper A.

46. VAGLE, G.B., HURST, A., DYPVIK, H. 1994. Origin of quartz cements from the Jurassic of the Inner Moray Firth (UK). Sedimentology 41, 363-377.

45. VERSTRALEN, I. and HURST, A. 1994. Sedimentology, reservoir characteristics and exploration potential of the Rona Sandstone, west of Shetland. First Break 12, 11-20.

44. TREWIN, N.H. and HURST, A. 1993. Geology of East Sutherland and Caithness, Geological Society of Aberdeen, Scottish Academic Press, 182p.

43. HURST, A. 1993. Bathonian to Oxfordian strata of the Brora area. In: Geology of East Sutherland and Caithness (N.H. Trewin & A. Hurst eds.), Geological Society of Aberdeen, Scottish Academic Press, p.47-74.

42. SUTHERLAND, W.J., HALVORSEN, C., HURST, A., McPHEE, C.A., ROBERTSON, G., WHATTLER, P.R and WORTHINGTON, P.F. 1993. Recommended practice for probe permeametry. Marine and Petroleum Geology 10, 309-318.

41. HURST, A. 1993. Production. In: Introduction to the Petroleum Industry, University of Aberdeen, 13p.

40. HURST, A. 1993. Sedimentary flow units in hydrocarbon reservoirs: some shortcomings and a case for high-resolution permeability data. Spec. Publication Int. Ass. Sediment 15, 191-204.

39. HURST, A. 1992. Routines. Innovation and cost effectiveness in geological reservoir description. Advances in Reservoir Technology Conference, London, Octobeer 1992, IBC, p.28.

38. HURST, A., GRIFFITHS, C.M. and WORTHINGTON, P.F. 1992. Geological Applications of Wireline Logs II. Special Publication of the Geological Society of London 65, p.406.

37. BLOODWORTH, A.J., HURST, A. and MORGAN, D.J. 1990. Detection and estimation of low levels of kaolinite by evolved water vapour analysis. Proceedings of the 9th International Clay Conference, 143-148.

36. LOWDEN, B., BRALEY, S., HURST, A. and LEWIS, J. 1992. Sedimentological studies of the Cretaceous Lochaline sandstone, NW Scotland. Geological Society Special Publication No. 62, 159-162.

35. NADEAU, P.H. and HURST, A. 1991. Application of back-scattered electron microscopy to the quantification of clay mineral microporosity in sandstones. Journal of Sedimentary Petrology 61, 921-925.

34. HURST, A. and ROSVOLL, K.J. 1991. Permeability variations in sandstones and their relationship to sedimentary structures, In: Reservoir Characterisation II (eds. L.W.Lake, Carroll, H.B. Jr. and Wesson, T.C.), Academic Press, pp. 166-196.

33. HALVORSEN, c. and HURST, A. 1990. Principles, practice and applications of laboratory minipermeametry, In: Advances in Core Evaluation, Accuracy and Precision in Reserves Estimation (ed. P.F.Worthington), Gordon & Breach, pp. 521-549.

32. HENRIQUEZ, A., TYLER, K.J. and HURST, A. 1990. Characterisation of fluvial sedimentology for reservoir simulation modelling. Society of Petroleum Engineers Formation Evaluation, **211**, 212-216.

31. LEWIS, J., LOWDEN, B. and HURST, A. 1990. Permeability distribution and measurement of reservoir-scale sedimentary heterogeneities in sub-surface exposures of a shallow marine sand-body. IAS Field Trip guide, IAS Nottingham, p.72.`.

30. HURST, A. and NADEAU, P.H. 1990. Determination of clay microporosity in reservoir sandstones: application of quantitative electron microscopy to petrographic sections forr petrophysical evaluation. SPE 19456.

29. BJØRKUM, P.A., MJØS, R., WALDERHAUG, O. and HURST, A. 1990. The role of the late Cimmerian unconformity for the distribution of kaolinite in the Gullfaks Field, northern North Sea. Sedimentology 37, 395-406.

28. CLEMENTSEN, R., HURST, A.R., KNARUD, R. and OMRE, H. 1990. A computer program for evaluation of fluvial reservoirs. North Sea Oil and Gas Reservoirs-II, The Norwegian Institute of Technology (Graham & Trotman), 373, 374-385.

27. HURST, A., LOVELL, M.J. and MORTON, A.C. (eds.) 1990. Geological applications of wireline logs. Special Publication of Geological Society of London 48, pp.357.

26. HURST, A. 1990. Natural gamma-ray spectrometry in hydrocarbon-bearing sandstone from the Norwegian Continental Shelf. Geological Applications of Wireline Logs Geological Society Special Publication 48, 211-222.

25. MORTON, A.C., STIBERG, J.P., HURST, A. and QVALE, H. 1989. Use of heavy minerals in lithostratigraphic correlation, with examples from Brent sandstones of the northern North Sea. In: Correlation in Hydrocarbon Exploration, Norwegian Petroleum Society (Grraham & Trotman), p.217-230.

24. MILODOWSKI, A.E. and HURST, A. 1989. The authigenesis of phosphate minerals in some Norwegian hydrocarbon reservoirs: evidence for the mobility and redistribution of rare earth elements (REE) and Th during sandstone diagenesis. In: Water-rock interaction WRI-6 (ed. D.L. Miles). A.A. Balkema/Rotterdam/Brookfield, p.491-494.

23. HENRIQUEZ, A., TYLER, K.J. and HURST, A. 1988. Characterisation of fluvial sedimentology for reservoir simulation modelling. Society of Petroleum Engineers, 611-620.

22. HURST, A. and MORTON, A.C. 1988. An application of heavy-mineral analysis to lithostratigraphy and reservoir modelling in the Oseberg Field, northern North Sea. Marine and Petroleum Geology 5, 157-170.

21. BJØRKUM, P.A, WALDERHAUG, O. and HURST, A. 1987. Kaolinite in North Sea Jurassic Sandstones. Rogaland Research Sector for Petroleum Geology, SPOR Seminar 16-17 Sept. p.3.2.1 - 3.2.12.

20. HURST, A. 1987. Problems of reservoir characterisation in some North Sea sandstone reservoirs solved by the application of microscale geological data. In: North Sea Oil and Gas Reservoirs (eds. Buller, A.T. et al.), p.153-167.

19. ARCHER, J.S. and HURST, A. 1986. Evaluation of formation damage in heterogeneous reservoirs. Marine and Petroleum Geology Vol. 4, 119-126. 0264-8172/87/020119.

18. HURST, A. 1987. Mineralogical analysis and the evaluation of the petrophysical parameter. V_{shale} for reservoir description. Marine and Petroleum Geology 4, 81-92. 0264-8172/01068-10.

17. HURST, A. 1985. Reservoir description - some applications of sandstone diagenesis. Uppsala Symposium Clay Minerals - Modern Society, p.111-121.

16. HURST, A and ARCHER, J.S. 1986. Some applications of clay mineralogy to reservoir description. Clay Minerals, **21**, 811-826.

15. HURST, A. and ARCHER, J.S. 1986. Sandstone reservoir description: An overview of the role of geology and mineralogy. Clay Minerals, **21**, 791-809.

14. HURST, A. and BJØRKUM, P.A. 1986. Thin section and S.E.M. textural criteria for the recognition of cement-dissolution porosity in sandstones. Sedimentology 33, 605-614.

13. HURST, A. 1985. The implications of clay mineralogy to palaeoclimate and provenance during the Jurassic in NE Scotland. Scottish Journal of Geology 21, 143-160.

12. HURST, A. 1985. Mineralogy and diagenesis of Lower Jurassic sediments of the Lossiemouth borehole, north-east Scotland.. Proceedings of the Yorkshire Geological Society 45, 189-197.

11. STOUT, A.M. and HURST, A. 1985. X-ray diffraction of early iron age pottery from Western Norway. Archaeometry 27, 225-230.

10. HURST, A. 1985. Diagenetic chlorite formation in some Mesozoic shales from the Sleipner Area of the North Sea. Clay Minerals 20, 69-79.

9. HURST, A. and BULLER, A.T. 1984. Dish structures in some Palaeocene deep-sea sandstones (Norwegian sector, North Sea): Origin of the dish forming clays and their effect on reservoir quality. Journal of Sedimentary Petrology 54, 1206-1211.

8. IRWIN, H. and HURST, A. 1982. Applications of geochemistry to sandstone reservoir studies. In: Petroleum Geochemistry and Exploration of Europe (ed. J. Brooks), Special Publication of the Geological Society of London 12, p.127-146.

7. HURST, A. 1982. The clay mineralogy of Jurassic shales from Brora, NE Scotland. In: International Clay Conference 1981 (eds. H. Van Olphen and F. Veniale), Developments in Sedimentology 35, Elsevier, p.677-684.

6. HURST, A. and IRWIN, H. 1982. Geological modelling of clay diagenesis in sandstones. Clay Minerals, **17**, 5-22.

5. HURST, A. 1981. Mid Jurassic stratigraphy and facies at Brora, Sutherland. Scott. J. Geol., **17**, 169-177.

4. HURST, A. 1981. A scale of dissolution for quartz and its implications for diagenetic processes in sandstone. Sedimentology (1981) **28**, 451-459. ISSN 0037-0746/81/0800-0451

3. HURST, A. and DURHAM, J.J. 1980. Isotope Geology Unit, Stable Isotope Report No. 42. Isotopic zoning in authigenic quartz.

2. HURST, A. 1980. Geology of the Hawksmoor Nature Reserve. Special Publication for the National Trust of England and Wales.

1. HURST, A. 1980. Occurrence of corroded authigenic kaolinite in a diagenetically modified sandstone. Clays and Clay Minerals 28, 393-396.

Rule 26 Disclosure

Rule 26(a)(1)(A)(i):

Name: Andrew Hurst

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Subject Matter: Thermal Structure of Sedimentary Basins, Golden Zone, Encountering Overpressure During Drilling, Exploration Drilling in Unstable Submarine Strata-The Geological Context of the Macondo 252 #1 Well, Are Drilling Problems Encountered in Macondo 252 #1 Unique to a Restricted Area of the Mississippi Submarine Canyon, HPHT Definition-Global Learning from Macondo 252 #1, LOP's

Rule 26(a)(2)(B):

Rule 26(a)(2)(B)(i): A complete statement of all opinions the witness will express and the basis and reasons for them:

See: FINAL REPORT

Rule 26(a)(2)(B)(ii): the facts or data considered by the witness in forming them:

Reliance Documents:

See References List – Appendix A

See Figure Lists – Appendix A

NOTE: All Reference List pages and Figure List figures will be produced in supplemental production. MDL 2179 reliance material is indicated in Reference List and will also be included in supplemental production.

Rule 26(a)(2)(B)(iii): any exhibits that will be used to summarize or support them:

See Presentation – Appendix B

Rule 26(a)(2)(B)(iv): the witness's qualifications, including a list of all publications authored in the previous 10 years:

Summary of Witness' Qualifications:

See Curriculum Vitae of Andrew Hurst – Appendix A

List of All Publications Authored:

See Curriculum Vitae of Andrew Hurst – Appendix A

Rule 26(a)(2)(B)(v): a list of all other cases in which, during the previous 4 years, the witness testified as an expert at trial or by deposition:

None.

Rule 26(a)(2)(B)(vi): a statement of the compensation to be paid for the study and testimony in the case.

$300 GBP per hour + expenses