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A critical review of currently available pore pressure methods and their input parameters.
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Glaciations and compaction of North Sea sediments.

By

Carl Fredrik Gyllenhammar

This thesis was submitted as the fulfilment of the requirements for the degree of Doctor of Philosophy

Abstract

Historically pore pressure evaluation in exploration areas was based on empirical relationships between drilling parameters, wireline logs and the mud weight. Examples include Eaton's Ratio and the Hottman & Johnson Methods, which were based on data from the Gulf of Mexico. These methods are not readily transported to other areas, such as the North Sea Basin, where the sediments are different in character and where burial and temperature histories are distinctly different.

Data from several offshore North Sea wells, with high quality wireline and associated data have been analysed to determine the most appropriate method to estimate pore pressure in mudrocks. The data have led to an understanding of the key parameters for successful pore pressure estimation. The most effective method is shown to be the Equivalent Depth Method, but only where disequilibrium compaction is the source of the overpressure in the mudrocks.

Core samples from 576 British Geological Survey sites in the offshore area of the British Islands were compared with >10,000 porosities collected from the deep oceans (DSDP/ODP sites), which show that the porosities in the shallow section in the North Sea are anomalously low. The shallow section of the North Sea includes large volumes of Pleistocene-Recent sediments deposited as glacial and inter-glacial deposits. Frequency analysis (Cyclolog) of the wireline data covering this interval in several North Sea wells revealed a pattern in the relative featureless original data. Comparison with the global signature for oxygen isotopes for the same time period suggests that there have been ten cycles of ice sheet build up (Glacial period) followed by melting (Interglacial period) during the last one million years. Glacial deposits from 10 individual glacial cycles have therefore been identified in several exploration wells in the North Sea. Implications of loading/unloading of ice for the migration and trapping of hydrocarbons in the North Sea Basin are assessed.

Acknowledgements

First I must thank my supervisor, Richard Swarbrick (Dick). I met Dick first time in December 1995 in London. It was the first GeoPOP meeting I attended representing Norske Conoco. When a year later I expressed interest in doing a PhD at the university of Durham, his enthusiasm, despite my age, made what was laying ahead possible. My wife Marit and I left our jobs late 1998, we sold our house in Stavanger and moved to Durham with our two children, Elen-Martine and Fredrik.

At the university I found Dick's continues support and interest in my subject as well as the requirement to deliver regular reports to GeoPOP an assurance for continued progress. Neil Goulty was never far away to discuss any difficult equation. Both his and Dick's enthusiasm for my "ice theory" made this thesis what it is. I had also help from Fred Wollard's long experience with using principle component analysis. The last year in Durham I was lucky to share an office with Martin Traugott. He shared his long experience in pore pressure prediction as well as his own developed software PresGraf with me.

My thanks also goes to Norske Conoco, in particularly James Middleton. They supplied the well data I used as well as providing financial support for the project. Thanks go to all those from GeoPOP who were there to help and exchange ideas, Toby, Paul, Daniel, Neville, Gareth Yardley, Andy Aplin and Yunlai Yang.
Finally many thanks to my new colleges at BP, for their support during the last year, Nigel Last, Mark Alberty and Mike McLean.

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Declaration

The content of this thesis is the original work of the author (other people's work, where included, is acknowledged by reference). It has not been previously submitted for a degree at this or any other university.

Carl Fredrik Gyllenhammar
Durham
September 2003

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Chapter 1 Introduction

1.1 Background

Fifteen years ago, most pore pressure studies were undertaken solely for safety aspects in the design and drilling of exploration wells. As the need for accurate pore pressure evaluation is growing due to its general application in exploration studies such as hydrocarbon migration studies, more accurate methods founded on sound physical principles, and not just empirical observations, are needed.

Pore pressure estimation is a particular challenge in the North Sea on account of the complex tectonic and sedimentological history of the region, where the highest overpressure (pore pressures above the normal, hydrostatic pressure) are found in Jurassic and Triassic reservoir sandstones. The presence of a thick Chalk section as well as a variety of mudrock types, including a kerogen-rich petroleum source rock, challenge standard practices for pore pressure evaluation which were, in many cases, developed in the Gulf of Mexico where the rocks are younger and exclusively siliciclastic (sandstone, siltstones and shale mudrocks). The late history (Pleistocene-Holocene) of the North Sea has involved ice loading and the deposition of glacially-derived sediments which add a further component of complexity to the stress and fluid history of North Sea sediments.

The availability of a very high quality set of well data from the Norwegian North Sea (Central Graben) provided impetus for this project which was designed to test current methods of pore pressure prediction, assess the impact of a late ice-loading and unloading history and apply new technology on mudrock compaction (being concurrently developed in the GeoPOP research group – see below).

There are a number of complementary data which can be used for pore pressure evaluation including basin modelling, seismic velocities, wireline logs and drilling parameters. Each requires different data input and interpretation requirements. In this thesis the emphasis is for pore pressure evaluation using wireline logs. The response from the drilling parameters was used as an independent control.

The thesis was funded by Norske Conoco in Norway and the work was included as part of GeoPoP. GeoPoP (GEOsciences Project into OverPressure) was a joint research project involving University of Durham, Newcastle University, Heriot Watt University and industrial sponsors such as major oil companies like BP, Amoco, Statoil, Norsk Hydro, Phillips, Conoco, etc. The aim of GeoPOP was to explain how pore pressures evolve in mudrocks and to evaluate and develop new methods to predict and calculate the pore pressure in these sediments.

1.2 Data

Norske Conoco made most of the data available, consisting of wireline data from exploration wells. The most important well was 1/6-7, drilled by Norske Conoco in 1989, which is classified as a high pressure (>10,000 psi) and high temperature (>350ºF) (HPHT) well. In addition to well 1/6-7 were a number of offset wells in the southern part of the Norwegian shelf. The data set included also some wells from Haltenbanken and the Barents sea. Well 1/6-7 has high quality wireline and mud logging data particularly with respect to testing pore pressure prediction and calculation methods (Figure 1.1, 1.2 and 1.3).

GeoPOP provided the data from the Gulf of Mexico. Data from the shallow coring project by British Geological Survey (BGS) were provided by BGS. Data from the Ocean Drilling Project (ODP) are freely available on the Internet and were downloaded free of any charge.

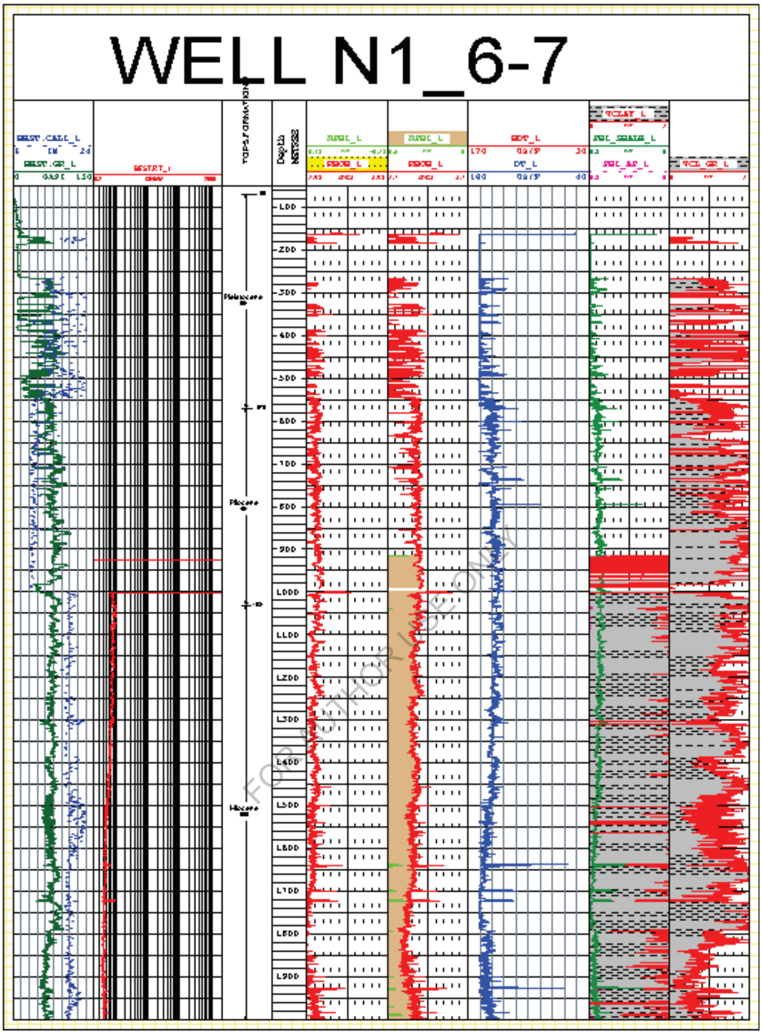

Figure 1.1 The wireline log plot of well 1/6-7 from seabed to 2000m.

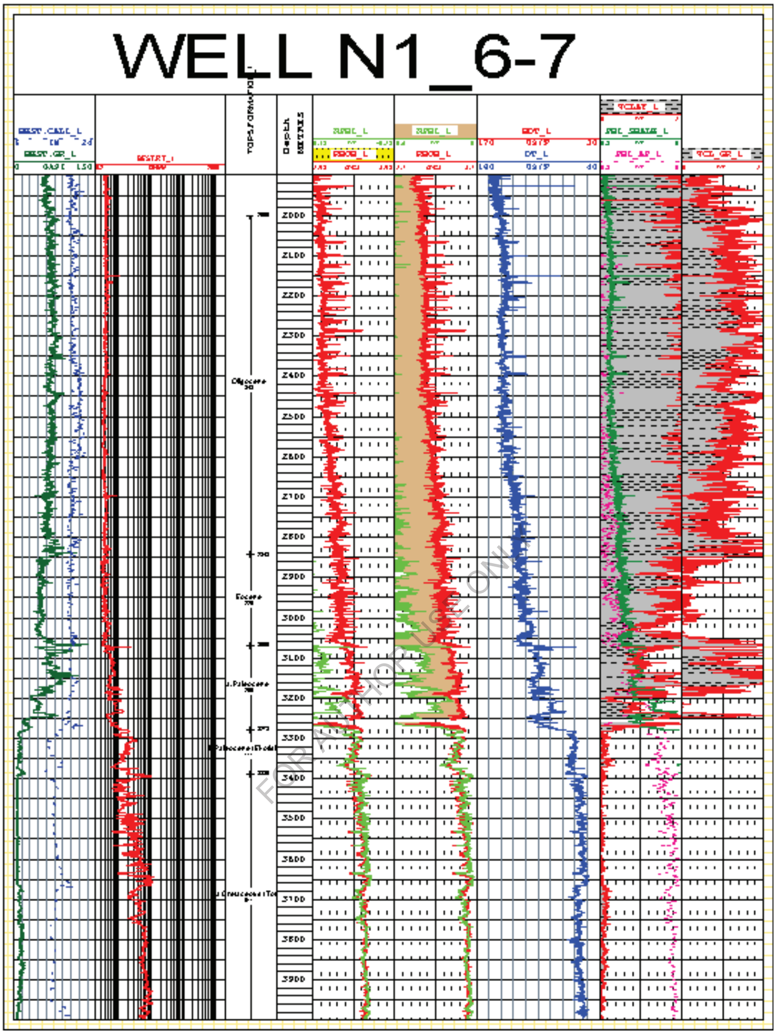

Figure 1.2 The wireline log plot of well 1/6-7 from 1900 to 4000m.

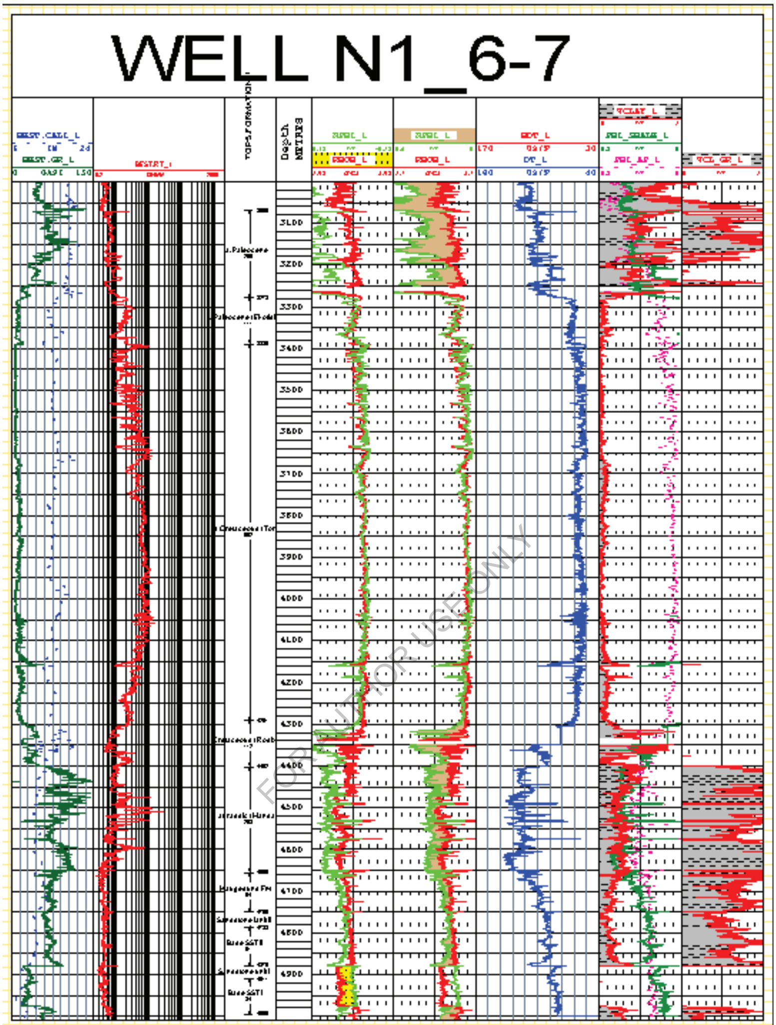

Figure 1.3 The wireline log plot of well 1/6-7 from 3000 m to 4995 m (TD).

1.3 Introduction

In exploration drilling operations pressure from the circulating drilling fluid (mud) is used to prevent the pore fluid in the porous rock entering the borehole. The pressure from the mud at a particular depth is a function of the average density (MW = Mud Weight) and the vertical height of the column from that depth to the surface. In low permeability formations, such as mudrocks, the formation can cave into the wellbore through tensile failure if the pore pressure is higher than the counter pressure from the mud. The industry has a long history of establishing empirical relationships between drilling parameters such as the rate of penetration and the gas measured in the returning drilling fluid to the pore pressure in the mudrocks. The uses of drilling parameters are very subjective and prone to large uncertainties. The pressure can also be calculated indirectly from petrophysical measurements. Petrophysical data can be acquired while drilling or after drilling a section. In the former case the petrophysical sensors are placed behind the drill bit in operations known as Logging While Drilling (LWD) or Measurement While Drilling (MWD). When data is acquired once drilling has been completed, the petrophysical sensors are lowered down the hole suspended from a wire (wireline logging) and readings taken by the tools while being reeled back up. The pore pressures in the reservoir rocks with high permeability are measured directly using a wireline tool with a pressure gauge. A cylindrical probe with a small aperture is hydraulically forced into the formation (Figure 1.4) and the tool remains at the location until the pressure stabilizes between the inside of the tool (where the pressure gauge is located) and the formation (where the probe has been extended). The pressure is recorded as pressure vs time. The most common trade acronyms for these tools are RFT (Repeat Formation), FMT (Formation multi-tester) or MDT (Modular Dynamics Tester). In mudrocks where permeability is very low, this tool cannot be used due to the time it will take for pressure to stabilize. Direct pressure measurements are also recorded when a hydrocarbon zone is tested, called a Drill Stem Test (DST).

The accompanying petrophysical measurements collected at the same time as the pressure tests include sonic, velocity, neutron porosity, density, and resistivity (unless you intended to list something else). These sensors are all calibrated for the porous formation and will tend to give erroneous reading if any clay minerals are present.

The challenge is therefore to use these measurements in mudrocks with low permeability and high clay content. During compaction of compressible sediment, such as mudrock, water is expelled and the porosity decreases. If the free water which needs to be expelled to maintain equilibrium with the imposed stresses cannot drain out of the system, the porosity will not decrease, with the result that the pore pressure increases above the hydrostatic pressure. Porosity cannot be measured directly in a borehole. The porosity is calculated indirectly from the sonic velocity, neutron porosity, density or the resistivity measurement, or a combination of these measurements. The effective or inter-granular stress is then calculated using a relationship between the porosity, the normal compaction trend and the total lithostatic stress (overburden stress).

A variety of empirical relationships have been developed for calculating mudrock porosity from different log responses. Typically, a stress-porosity relationship is not used directly, but instead porosity is compared against a normal compaction trend, which would be the porosity against depth for the location in question assuming a 'normal' pressure profile equivalent to the hydrostatic head of a water column. In this work it will be shown that the normal compaction trend often yields the biggest uncertainties in calculating the pore pressure in mudrocks.

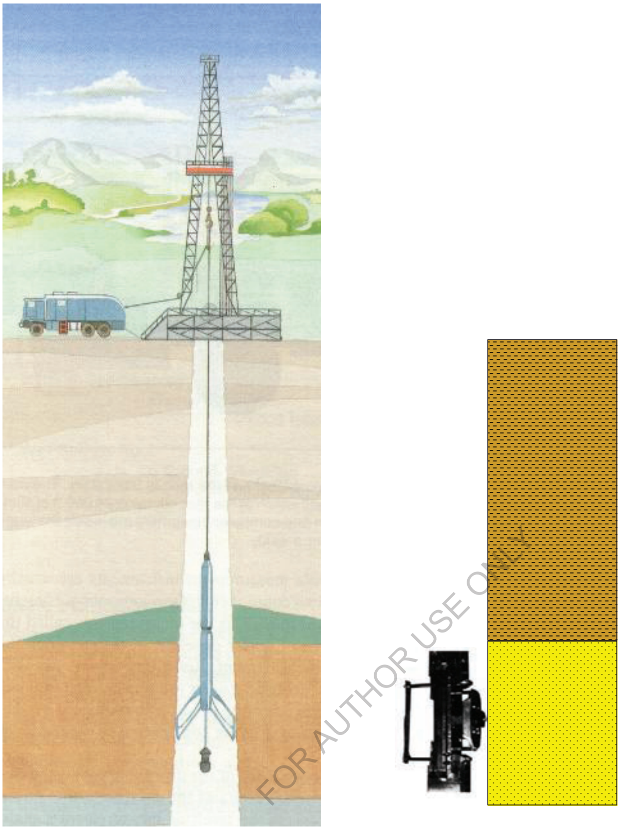

Figure 1.4 Schematic of wireline logging. The lithological column to the right is a schematic of a pressure probe (RFT) being used to measure the pore pressure in permeable sandstone.

Having inferred mudrock porosity from logs and computed or established a normal compaction trend of expected porosity for normal pressure, the final step is to find a relationship quantifies the pore pressure magnitude associated with a mismatch between the estimated mudrock porosity from log response and the normal compaction trend.. This transform or equation might be based on physical principles, such as the equivalent depth (or effective stress) method, or empirical relationships, such as the Eaton’s method. It will be shown that the transform method used for calculating the pore pressure is less important than the choice of normal compaction trend.

The initial goal for this research was to establish a new method to calculate the pore pressure in mudrocks as a function of petrophysical measurements. During the course of this research it became apparent that the classical equivalent depth method is a reliable equation and it would be of limited value to attempt an improvement to it. Also, the porosity of the mudrocks can be reliably calculated from a combination of the available wireline logs. A sensitivity study shows clearly that the biggest uncertainty is the normal compaction curve. Eaton (1975) summarized it best: “The methods used to establish normal trends vary as much as the number of people who do it”.

A normal compaction curve represents the reference trend describing the compaction behaviour of sediments which are normally pressured. The compaction (porosity loss involving expulsion of fluids) is caused by increases in vertical and /or horizontal stress. Conventional pore pressure prediction uses the normal compaction curve to estimate the magnitude of overpressure. Data from which normal compaction curves are derived include shallow buried sediments of the same age and lithology, or published compaction relationships. For example, Hansen (1996) examined three wells in the North Sea where he assumed that the mudrocks have normal pore pressure. He established a relationship between the sonic travel time and the mudrock porosity used in this research. Other approaches are based on laboratory measurements of compaction such as by Skempton (1970) where he showed a relationship between compaction and the volume of fine-grained material in the samples. The shortcoming of that approach is that the relationship does not take into account the different compaction behaviours of clay minerals such as montmorillonite versus fine-grained quartz, (K. Bjorlykke (2001) personal oral commun.).

This research shows that it is unlikely that any useful normal compaction trend can be established in the North Sea due to **recent glacial events**. The glacial tills left by a earlier glacial event have been overlooked for many years. The nature of these sediments is found to be very different from normal marine and non-marine shale mudrocks. This suggest that the previous method of establishing a normal trend by overlaying a number of porosity curves form offset wells will give wrong results if used in basins such as the North Sea.

1.4 Pressure, the basic concepts

Fluids differ from solids in that they are unable to support shear stress. When a body is submerged in a fluid such as water, the fluid exerts a force perpendicular to the surface at all locations around the surface of the body. If the body is small enough so we can neglect any differences in the vertical water column, the force (F) per unit area (A) is the same in all directions. This force per unit area is called the pressure P of the fluid:

$$P = F / A \qquad \text{[E1.1]}$$

The SI unit of pressure is Newton per square meter (N/m^2), which is called Pascal (Pa). The equivalent imperial unit is pounds per square inch (psi = lb/in^2).

Liquids found in rocks in the subsurface are relatively incompressible. This means that the ratio of mass to volume, called density is approximately constant. For a liquid whose density is constant, the pressure increases linearly with depth. The pressure P at any point in a liquid column is:

$$P = P_0 + \rho \text{ x } g \text{ x } h \qquad \text{[E1.2]}$$

P is the pressure at the surface and h is the vertical liquid column. The Greek letter ρ (rho) is the density. Density has the unit mass/volume (kg/m^3 = g/cm^3). g is the acceleration due gravity at the earth surface and equal to 9.81 m/s^2.

Figure 1.5 shows a simplified diagram of how pore pressure may increase in a well. The hydrostatic pressure (often called the normal pressure) in sediments underlying the ocean often follows a gradient equal to 0.0101 MPa/m. That is the increase in hydrostatic pressure in water with an average density of 1.03 g/cm^3. The overburden pressure is the pressure exerted by all overlying material, both solid and fluid. Below the water bottom, this line approximates 0.0226 MPa/m (1 psi/ft) in a clastic sedimentary environment. The pore pressure is the pressure of the fluid in the pore space of the rock. It may be equal to or higher than the hydrostatic pressure, but not higher than the overburden pressure (Figure 1.5). If the pore pressure approaches the overburden pressure the rock will fracture and release fluids. However, often fracturing will occur at a lower pressure, equivalent to the least principal stress, which in an extensional basin is less than the overburden (the vertical stress). If at a specific depth of burial the mudrock permeability becomes so low that the excess water from normal compaction can no longer flow out of the system as fast as the rate of new sediments, the pore pressure will increase. The maximum increase of pore pressure by this mechanism called disequilibrium compaction (Swarbrick and Osborne, 1997)- and is often found to be parallel to the lithostatic gradient (Clayton and Hey, 1994), indicating, at depth, transfer of most/all of the load onto the pore fluid, with very little/no increase with vertical effective stress..

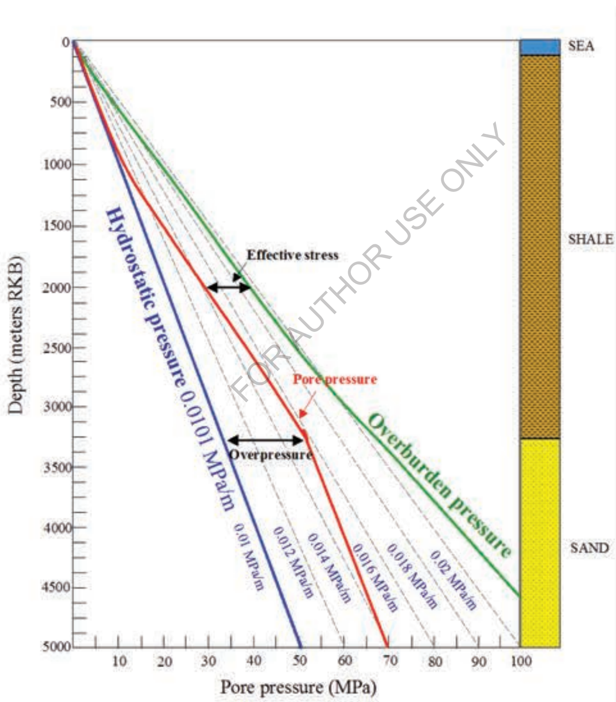

Figure 1.5 Pressure plotted against depth in a fictional well. The effective stress is equal to the overburden pressure minus the pore pressure and the overpressure is equal to the pore pressure minus the hydrostatic pressure.

In a borehole, the pressure exerted by the drilling fluid to either prevent influx of pore fluids from the formation or prevent hole caving instability is equivalent to density of the drilling fluid and its column height. Therefore, the formation pore pressures are often converted into drilling fluid density equivalents so it is clear as what drilling fluid density just balances the pore pressures. Figure 1.6 shows how a typical pore pressure profile can be displayed as pressure gradient versus depth. If one follows the change in the pressure gradient of the pore pressure (red curve), every point on the curve represents a pressure gradient and a corresponding average fluid density that particular pressure at that depth represents. The maximum pore pressure gradient is reached at the top of the reservoir (3200 meters) equal 0.016 MPa/m. That is equivalent to the pressure at the bottom of a 3200-meter vertical fluid column with an average fluid density of 1.64 g/cm^3. In exploration drilling a drilling mud is used where materials such as barite is mixed to form a liquid (called drilling mud) with such high average density. The terminology used is equivalent mud weight (EqMW). The pressure gradient plot illustrates a big challenge while drilling these wells. The EqMW has to be high enough to hold back the fluid from the depth where the formation has the highest-pressure gradient. However, in some formations, typically the shallower ones, this mud density would apply a pressure significantly greater than the pore pressures in these formations. This excess pressure may lead to fracturing of the rock and losses of the drilling fluid.

A confusing aspect in the oil industry with regard to pressure terminology is the mixing the terms; pressure gradient and density (EqMW). This becomes particularly difficult and confusing when working with a mixture of both imperial and the SI units. It has already been shown that the pressure gradient equals density multiplied by the acceleration due to gravity. In the imperial system, the norm is to use **weight density** rather than density. Weight density is defined as the ratio of the weight of an object to its volume. The units are pounds per gallon (ppg). As the weight is equal to the mass multiplied with gravity, both weight density and pressure gradient have the same units. The imperial unit system has historically been the norm in the oil industry and the people involved has become used to converting directly from weight density (ppg) to pressure gradient (psi/ft) and to pressure (psi). The word weight density is often shortened to density. This has created a problem when converting to the SI system. Too often, while converting from density (g/cm^3) to pressure gradient (MPa/m), density is not multiplied by gravity (9.81 m/s^2). A typical example is a recent paper titled “Pore Pressure terminology” in the Leading Edge written to explain the problem, but failing to explain the difference between weight density and density (Bruce and Bowers, 2002).

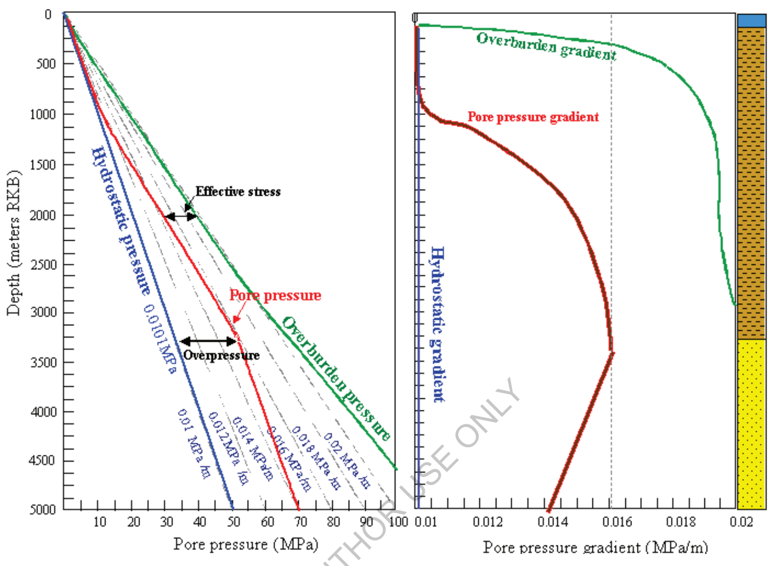

Figure 1.6 The Figure to the right shows how a pressure versus depth plot (left, Figure 1.5) becomes presented as pressure gradient versus depth.

1.5 Aims and layout of thesis

The aims and objective of this thesis are to:

1. Develop a critical review of current methods used to calculate the pore pressure in mudrocks.
2. Establish the uncertainties of the input variables using in principle component analysis, applied to the wireline measurements with reference to the mudrock porosity calculated and the drilling parameters with reference to the calculated drilling exponents.
3. Identify the variables that have the biggest impact on the estimation of pore pressure, and how they can be improved.

4. Compare the wireline signature of overpressured shales in the North Sea basin with those from the Gulf of Mexico.
5. Examine why the resistivity measurements of the mudrocks can be used as input parameter to calculate pore pressure in the Gulf of Mexico, while this has proved difficult to apply in the estimation of pore pressure in the North Sea.

Following the introduction comes Chapter 2 where the pressure concepts with respects to pore pressure in shallow sediments are discussed. That is followed by a discussion of mudrock porosity and normal compaction in mudrocks. Then the different pressure calculation methods, first with wireline logs as input, then those using drilling parameters.

Chapter 3 discusses the results from using these different pore pressure estimation methods on a test well, Nor 1/6-7 in the North Sea. The sensitivity of the input parameters are discussed. The results from the North Sea are then compared with the mudrocks from a mini-basin in the Gulf of Mexico,

Chapter 4 examines the glacial history of the North Sea to explain the nature of the shallow sediments, and their physical and petrophysical properties. Use of a novel application of the software Cyclolog has helped in characterising the glacial sediments. Finally the relevance of the glacial history of the North Sea is reviewed in relation to the petroleum system which has generated productive oil and gas fields .