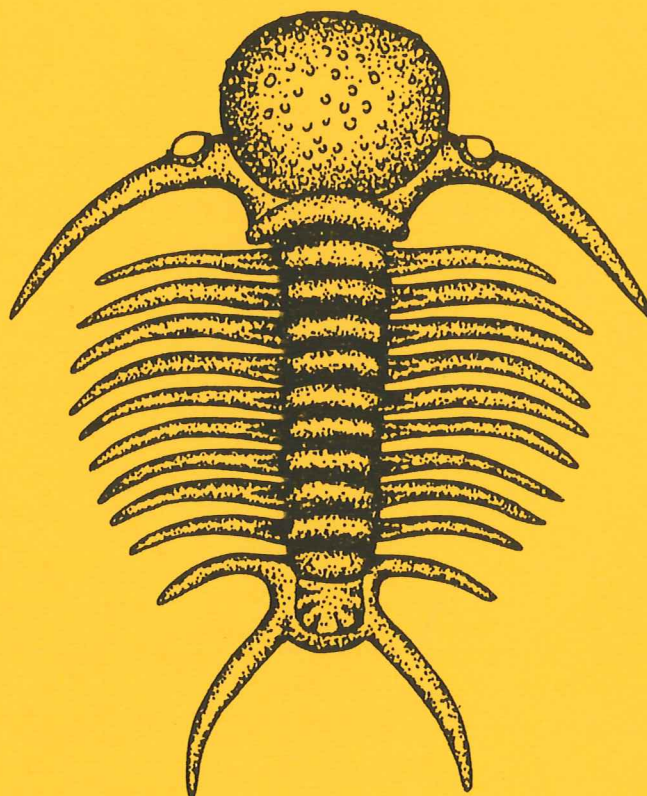


# EXAMENSARBETE I GEOLOGI VID LUNDS UNIVERSITET

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GEOBIBLIOTEKET  
PERIODICA

Historisk geologi och Paleontologi

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Modelling of reservoir quality in quartz-rich  
sandstones of the Lower Cretaceous Bentheim sandstones,  
Lower Saxony Basin, NW Germany

Howri Mansurbeg

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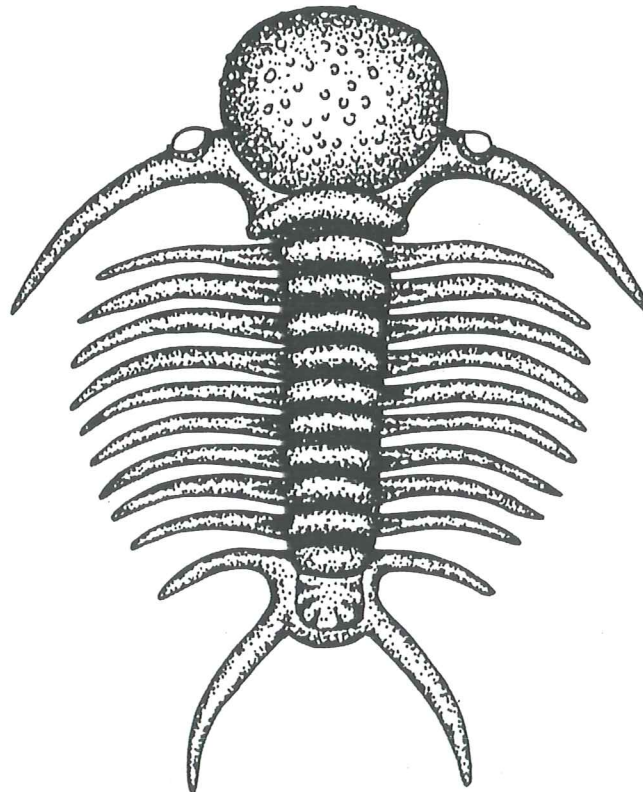
Nr 143

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Howri Mansurbeg

Mansurbeg, H., 2001: Modelling of reservoir quality in quartz-rich sandstones of the Lower Cretaceous Bentheim sandstones, Lower Saxony Basin, NW Germany. Examensarbeten i Geologi vid Lunds Universitet, Historisk Geologi och Paleontologi Nr 143, pp 1-35 (in cooperation with the Department of Energy and Resources at the Technical University of Denmark).

The Lower Cretaceous Bentheim sandstones of the Lower Saxony Basin in Northwest Germany (one of the main onshore oil fields of Western Europe) are mature quartz arenites in terms of texture and mineralogy. This study shows that the mineralogical maturity to a large degree is the result of diagenetic processes. Hence, the present day detrital composition and texture is not what they were at the time of deposition. The sandstones are highly porous and permeable and show presence of quartz cement as overgrowths which cement the sandstone, partly dissolved detrital feldspar grains, oversized pores caused by complete feldspar dissolution and authigenic kaolinite-dickite booklets. The porosity and permeability have been measured in the laboratory. The results were combined with the observations made by conventional optical microscopy and quantification of detrital and diagenetic components-textures by point counting, cathodoluminescence petrography, and back scattered electron imaging. These techniques have been undertaken in order to assess the impact of the presence of quartz overgrowths and feldspar dissolution on porosity and permeability. XRD analyses were done for identifying the mineralogy of the main detrital and diagenetic components, in particular for detrital and authigenic clay minerals. Quartz cement in the form of syntaxial overgrowths on detrital quartz grains played an important role in determining the petrophysical properties in the Bentheim sandstones. This kind of cement usually causes harmful reductions in porosity and permeability. However, in the Bentheim sandstones quartz cementation possibly had a positive impact in terms of porosity preservation. Cement precipitated in limited amounts and probably helped the reservoir framework to withstand the destructive effect of overburden pressure and consequent mechanical compaction. The study shows that detrital quartz grains were important, and that possibly the different types of quartz grains had different susceptibility in terms of acting as host grains for precipitation of authigenic quartz. The presence of detrital feldspar and its composition was another major parameter during diagenesis and consequent porosity-permeability modification. Dissolution of feldspars may have been an important internal (local) source of silica and aluminium for kaolinite-dickite authigenesis and possibly also for quartz cementation, and created oversized secondary pores.

**Keywords:** Permerability, Porosity, Diagenesis, reservoir characteristics, Bentheim sandstones, Cretaceous.

*Howri Mansurbeg, Department of Geology, Historical Geology and Palaeontology, Sölvegatan 13, SE-22362 Lund, Sweden.*

## Introduction

Petrophysical properties of reservoir sandstones are the combined result of depositional and diagenetic processes. Porosity and permeability are a function of depositional texture (grain size, grain size distribution, packing density, and grain orientation). Grain size and sorting largely control porosity, whereas textural anisotropy as a function of grain orientation and sedimentary structures are additional controls on permeability. However, diagenetic processes tend to modify the primary texture by processes such as cementation, dissolution and compaction. In quartz-rich sandy sediments quartz cementation is a main diagenetic process influencing reservoir properties. Also dissolution of feldspars and lithic grains can be important and may modify the depositional composition. In a number of cases it has been recognised that quartz arenites owe their quartz-rich composition to dissolution of other clastic components during burial diagenesis (de Ros et al. 2000) and are in fact "diagenetic quartz arenites". The lower Cretaceous Bentheim sandstones in the Lower Saxony Basin in Germany is a quartz arenite with good reservoir quality, and include one of Western Europe's main onshore oil fields. In the present study the texture, composition and the petrophysical properties (porosity, permeability, density) of a Bentheim sandstones section were analysed and a correlation between textures, diagenetic features (and inferred processes) and reservoir properties was established. The aim of the present study was further to analyse the causes of the variability in petrophysical properties, and to relate the results to existing general diagenetic models. In addition, the quantitative results of the used analytical techniques were compared and evaluated.

## General factors affecting sandstone reservoir quality

Sandstone reservoirs in general inherit their qualities after more or less significant mineralogical and textural modifications through diagenesis, as a response to changing physical and chemical conditions during geological history of the basin (burial, uplift and denudation). As the tectonic situation changes through time, so do the physical and chemical conditions of the basin. The mineral phases within reservoir systems (both detrital and diagenetic) are in a continued race towards chemical equilibrium and tend to adapt to the new physico-chemical conditions. Every attempt to reach equilibrium is associated with complex chemical reactions (dissolution, replacement, precipitation, etc) which are largely responsible in modifying the main petrophysical properties (porosity and permeability). There is agreement upon a general decrease in porosity and permeability with depth and age. However, usually a great variability exists. The general trend may be a consequence of the general physical and chemical conditions. The variability, however, is most likely due to more local effects. Local control on diagenetic processes within the sediment may be exerted by texture, detrital composition, and sedimentary structures of the sandstone reservoirs and neighbouring shales. Porosity can be calculated directly from geophysical well logs, but permeability has to be inferred from porosity-permeability models, if not measured in cores. It is thus important to understand the fundamental relations between the two parameters and thus it is necessary to introduce both depositional and diagenetic processes into petrophysical models. There are many factors contributing to the outcome of sandstone reservoir properties encountered in oil fields that effectively modify the primary fabric and composition and subsequently reservoir quality (porosity-permeability). The influence of each parameter in each basin or perhaps in a certain hydrocarbon reservoir is relative. Burial history may be a major control in a particular basin (or in a part of the basin) whereas in another basin (or another part of the basin) detrital composition is playing the key role in reservoir quality modifications. In conclusion, sandstone hydrocarbon reservoirs are the result of complex physico-chemical processes. The geochemical systems involved are often considered open, thus diagenesis, which embraces all chemical, biological and mechanical post-depositional alterations, is even more complicated than the almost closed system conditions and diffusion controlled metamorphic systems. The local architecture of reservoirs and seals is another important issue, which is often not taken into consideration in petrophysical models. Most models give empirical trends for petrophysical properties and correlations between them (such as between porosity and permeability). These models are thus only valid for specific cases, basins etc. because of the multitude of local factors influencing the main diagenetic processes.

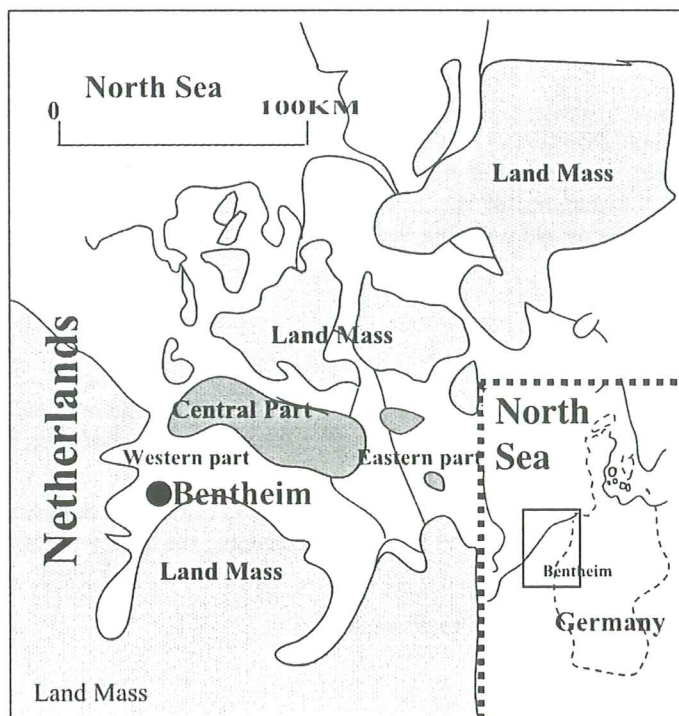
## The role of detrital composition

Typical reservoir sandstones are mainly composed of sand sized quartz, feldspar and rock fragments. Quartz and feldspar grains come from the weathering of source rocks such as granites or gneisses, or pre-existing sandstones. Rock fragments are derived from the weathering of any pre-existing rocks. The relative abundance of the detrital components is a function of palaeoclimate, tectonic activity in the clastic source area, the depositional environment and the processes acting in the sedimentary basin. In case of an arid climate in the source area, or rapid uplift and erosion rates, unstable sediment particles such as feldspars and most rock fragments can survive, leading to chemically immature sand compositions, which in turn are highly susceptible to diagenetic processes. In addition, physical (textural) immaturity is reflected by poor sorting and angular grains, and thus promoting poor later

reservoir conditions. Surviving chemically unstable grains tend to dissolve and form authigenic minerals and excess ions during diagenesis, which in turn can be included in newly formed cements. In contrast, the deposition of quartz-rich, diagenetically more stable sandstones is favoured under humid climatic conditions which favours the decomposition of feldspars by hydrolysis. Also, extended sediment residency and intense weathering in the source area, coupled to long transport distances (in particular in areas with tidal currents or longshore transport mechanical wearing of grains is intense) and limited tectonic activity favour the formation of quartz-rich sandstones. Consequently, mechanically and chemically stable grains such as quartz are likely to be frequently reworked and thus to become sorted and rounded, whereas other less mechanically stable grains (lithic grains and feldspar grains) are likely to be destroyed both by mechanical and chemical processes.

### The role of deposition and diagenesis

The petrophysical properties and reservoir quality of sandstones are the result of depositional processes and post-depositional changes to the primary texture, such as the precipitation of authigenic minerals in pre-existing pore spaces, or the dissolution of detrital framework or newly formed components resulting in redistribution of pore spaces or creation of new pore space. Especially the precipitation of cement is dependent on the availability of suitable nuclei in the form of detrital grains (often the cement has the same mineralogical composition as the nuclei), and suitable ion sources, either within the sandstone or for example within surrounding shales. Clastic grains within the sandstones may yield ions necessary for quartz cementation, through dissolution or replacement of detrital feldspar grains. On the scale of a sedimentary body and depositional sedimentary structures, the primary clastic composition changes according to the hydraulic conditions during and shortly after deposition, and mineralogical fractionation occurs due differences in fall velocity and hydrodynamic behaviour of each grain type. This leads to accumulation of specific grain types and minerals within certain sedimentary structures and facies. Hydrodynamic or aerodynamic conditions also lead to a variability in texture, grain packing, density and grain size distribution. Initial differences in porosity and permeability can thus be expected for different facies and even for different positions within a sedimentary structure. The variation in detrital composition as a function of grain size has been illustrated by Blatt et al. (1980) who established a relationship between sandstone detrital composition (mineralogy) and grain size. This may finally lead to different susceptibility of different facies to diagenetic processes (mechanical compaction, cementation, and chemical compaction), and thus to diagenetic differences and modification of the initial depositional properties and cause heterogeneity in the reservoir body.



*Fig. 1: Palaeogeographical reconstruction and present day location of the Bentheim sandstone (after Schott et al. 1967).*

## This study

In the present study the Lower Cretaceous Bentheim sandstones (Fig. 1) were used as an example for understanding the role of detrital composition on diagenesis and the impact of diagenesis on petrophysical properties. Seventeen samples have been taken from an active quarry in the Bentheim sandstones in Germany. The petrophysical properties (porosity, permeability, density) were measured and compared with quantitative and qualitative petrographic sandstone properties.

## Geological setting

The Lower Cretaceous Bentheim sandstones were deposited in the Lower Saxony Basin in Germany. The sandstones are medium grained, quartz-rich sandstones and occur together with minor conglomerate beds. The unit shows at places good reservoir qualities (measured permeability ranges up to 2 Darcy and the measured porosity is up to about 27%). Oil and gas reservoirs occur in the Netherlands (at Schoonebeek) and in Munsterland in northwest Germany, for instance the Rühlermoor field. The Schoonebeek field is one of the largest oil reservoirs on mainland Europe. The formation consist of up to five sandstone bodies separated by marine shales (Wonham et al. 1997). The age of the formation is Valanginian to Berriasian (Lower Cretaceous). The Bentheim sandstones form sheet-like and lenticular-shaped bodies which extended along the southwestern and southern margin of the lower Saxony basin during the Lower Cretaceous, in northwestern Germany to eastern Netherlands. The evolution of the

Lower Saxony basin began in response to North Sea crustal extension (rifting) in the late Middle to early Upper Jurassic (Parnell et al. 1996). The underlying Toarcian Posidonian Shale probably form the regional hydrocarbon source rock. The Bentheim sandstones was in its deepest parts buried to a maximum of about 3.5 km (Fig. 2). The Bentheim sandstones have been deposited along the margins of the Lower Saxony basin in shallow marine environments, in a number of coastal barrier-bar complexes and probably backbarrier muddy lagoons. The fine- to medium-sized quartz grains are well to fairly well sorted.

## Samples and facies

Seventeen samples were taken at an active quarry near the town Gildehaus, NW Germany (Table 1). Two additional samples were taken from a surface outcrop near Brochterbeck (Fig. 1). The sampled quarry wall at Gildehaus is oriented perpendicular to the main sediment transport direction (N-S) indicated by cross bedding. The samples were taken from three lithofacies, namely

1. Medium grained, massive – seemingly structureless thick-bedded sandstone (beds up to 3m thick). Sandstones appeared massive, probably due to small variation of grain sizes and lack of weathering in the quarry walls.
2. Trough cross-laminated, 0.2m to 1.0m thick sandstone beds.
3. Flaser-bedded and bioturbated fine grained sandstone (beds of up to 30cm thick).

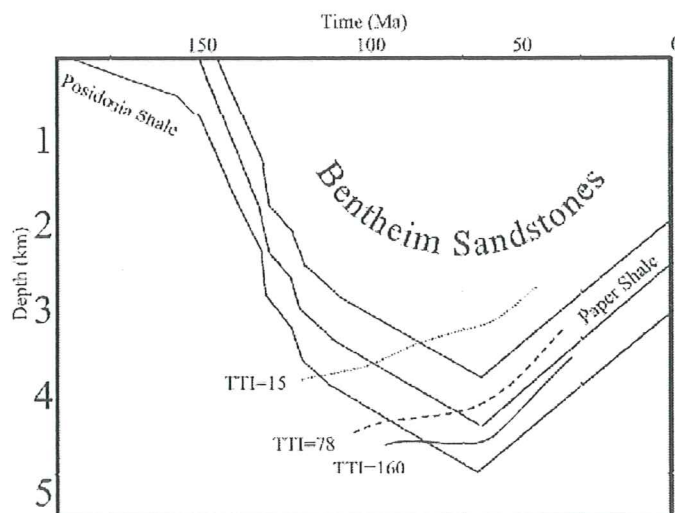


Fig. 2: Burial curve for the Posidonian Shale, which underlies the Bentheim sandstone (after Parnell 1995)

Table 1: Sample numbers and facies. The letter G refers to the Gildehaus quarry. B indicates samples from a weathered outcrop near the village Brochterbeck, where two samples have been taken.

Sample	Facies
G1	Massive sandstone
G2	Massive sandstone
G4	Cross bedded sandstone
G5	Cross bedded sandstone
G6	Cross bedded sandstone
G7	Cross bedded sandstone
G8	Cross bedded sandstone
G27	Cross bedded sandstone
G28	Cross bedded sandstone
G29	Cross bedded sandstone
G30	Cross bedded sandstone
G31	Cross bedded sandstone
G32	Burrowed, flaser-bedded sandstone
G33t	Massive sandstone
G33	Massive sandstone
B	Conglomerate
B2	Conglomerate

## Methods

### General aspects

The use of combined methods may reveal the reliability of each technique. This may lead to greater confidence and control over the obtained results. Petrophysical analyses consisted of determinations of effective porosity, permeability and grain density of the samples. The equipment used for these purposes was a Helium Gas Expansion Porosimeter HGP 100, and a Digital Gas Permeameter DGP 200, both designed by Edinburg Petroleum Services (EPS). Petrographical analyses were done for determination and quantification of detrital and diagenetic composition. They comprise conventional transmitted polarised light microscopy and standard point counting and analysis of back scattered electron micrographs, and cathodoluminescence microscopic images. The results were combined to establish diagenetic textures as well as temporal relationships, and when possible a quantification.

### Porosity measurements

The EPS Helium Gas Expansion Porosimeter is based on the principle of Boyle's Law, which states that for an ideal gas, at constant temperature, the product of its pressure and volume is a constant ( $PV = \text{constant}$ ). Therefore if a given quantity of gas expands into a larger volume, the expanded pressure  $P1$  and  $P2$  will be equal to initial pressure and volume  $P1$  and  $P2$  at constant temperature;

$$P1 V1/T2 = P2 V2/T2 \quad T1 = T2$$

The apparatus contain a core chamber, which seals the sample from atmospheric pressure. Its volume  $Vs$  is accurately known. The apparatus is also supplied with two reference volumes as standard, each of is selected by operation of valves  $V2$  and  $V3$ . Both these volumes can be opened giving a third reference volume. A cleaned, dried cylindrical sample with measured dimensions (length, diameter (cm) and weight (gm)) is placed in the sample holder, which is closed (compressed) using Nitrogen gas supply. After the sample is subjected to compression by Nitrogen, the selected reference chamber is opened to receive a Helium gas supply. After a short delay the gas supply is cut off in the reference chamber, by switching off the valve for the selected reference. On the electronic gauge a pressure value which corresponds to the reference pressure  $Pr$  (psig) is observed. Next step is to allow gas to expand into the core chamber, and a second pressure which represents  $Ps$  (psig) is observed. This pressure is the expanded pressure when the sample is placed in the chamber.  $Px$  is then measured, which is entered in a modified form of Boyle's Law;

$$P_r V_r = P_x (V_r + V_s - V_g)$$

Where:

$P_r$  = reference pressure (psig)

$V_r$  = reference volume ( $\text{cm}^3$ )

$P_x$  = expanded pressure (psig)

$V_g$  = grain volume ( $\text{cm}^3$ )

$V_s$  = volume of sample chamber ( $\text{cm}^3$ )

By rearranging the equation above the grain density ( $V_g$ ) can be obtained:

$$V_g = V_r + V_s - (V_s - P_r)/P_x \quad (1)$$

After the grain density is calculated, the simple equation:

$$\Phi = V_b - V_g/V_b \quad (2)$$

which is applied to calculate effective porosity.

In this context,  $\Phi$  is effective porosity,  $V_b$  is the bulk volume (measured independently in  $\text{cm}^3$ ), and  $V_g$  is the grain volume calculated using expression 1. This technique is considered one of the best methods of accurate and rapid determination of effective porosity (i.e., interconnected porosity). Effective porosity is related to rock permeability and a consistent and proportional relationship between permeability and effective porosity is to be expected. It is evident that such a relationship would not necessarily exist between permeability and ineffective (isolated) porosity. The use of helium is also advantageous because of the small atomic size of helium gas and the need to avoid gas adsorption.

### Permeability measurements

Absolute permeability was measured with a digital gas permeameter (designed by Edinburg Petroleum Services) with a Hassler-type core holder. Permeability is the ease of flow of a single fluid through a porous medium saturated completely with that fluid. Dried, cylindrical core plugs with known dimensions (1 inch diameter, minimum length of 1 inch) and weight have been used. Total Volume of the sample is measured by applying the equation;

$$V_t = d^2 h/4$$

The equation for permeability determination is modified from Darcy's law. The used expression is;

$$K = \mu \times Q_m \times P_a \times L / A \times \Delta P \times P_m$$

Where  $\mu$  is Nitrogen viscosity =  $(0,00005 \times T_g) + 0.0164$  Pa (ambient pressure) in atm, which can be measured at the atmospheric pressure on a mercury barometer,  $p_t$  (in mm Hg) according to the equation :

$$P_a \text{ (atm)} = P_t \text{ (mm Hg)} / 760$$

$L$  = Length in cm

$$A = \pi D^2/4$$

$\Delta P$  = (differential pressure), difference between core upstream ( $P_1$ ) and downstream ( $P_2$ ) pressure across the core.

$P_m$  is core mean pressure in atm.

$$P_m = (P_1 + P_2)/2 \text{ atm}$$

In case of FORWARD FLOW :  $P_1 = \Delta P \text{ (psid)} / 14,7 + P_a \text{ (atm)}$  and  $P_2 = P_a \text{ (atm)}$

In case of BACK FLOW :  $P_1 = (P_i \text{ (psig)}/14,7) + P_a \text{ (atm)}$

And  $P_2 = (P_i - \Delta P)/14,7 + P_a$



It is worth mentioning that this method only can be applied in case of laminar flow. In cases of non-laminar flow the method is unreliable. The method is applicable when a single liquid saturates the total porosity. A Klinkenberg correction was applied to all measurements. During the Klinkenberg correction the gas permeability is corrected for the effect of gas slippage phenomena, as the gas in contrast to fluid has the ability to slip into pore walls and consequently increase the measured permeability. Thus, a Klinkenberg corrected value is significantly lower than pre-corrected (gas permeability) values. The Klinkenberg effect is a function of the radius and tortuosity of pores in the measured samples. It was concluded by Klinkenberg (1941) that as mean gas pressure increase the permeability decrease. Using gas is probably advantageous. Gas is not reactive with the grains, so no dramatic changes in the pore geometry can be expected (which potentially could result in unrepresentative permeability values). A small gas molecule is capable of entering micro-pores and semi-isolated pores, which increase the reliability of the measurements. The Klinkenberg factor is different for different gases and it decreases as the liquid permeability increases (Heid 1950).

### Petrographical techniques

Polished thin sections were prepared and studied with a standard polarised-light petrographic microscope. The detrital and diagenetic components were quantified by point counting (300 counts per thin section). The same thin sections were studied by cathodoluminescence microscopy.

Luminescence is the emission of radiation due to excitation of atoms or molecules which jump to a higher energy state (quantum jump) and after a short delay time they (atoms or molecules) return to their former state of energy (Miller 1988). This generates detectable emissions, for instance of visible light, and alpha, beta or gamma rays. Cathodoluminescence (CL) is the process of emission of visible light when a specimen is bombarded by electrons. CL is further a function of time, temperature, current intensity and the voltage (potential difference, i.e., accelerating potential of the applied electron beam during electron bombardment of the sample). Basically, these factors do not show simple linear relationships. The physical and chemical environment of quartz crystallisation is perhaps playing a substantial role in controlling CL intensity. In this study, uncovered thin sections were studied using a cold cathode device mounted on a conventional transmitted polarised light microscope. The advantage of using uncovered polished thin sections is the possibility to obtain pairs of CL and standard polarised light images from the same view in the thin section.

We are only interested in the visible CL spectrum, which gives important clues to our understanding of complex diagenetic fabrics and the compositions of grains and cements. Lattice defects, and inclusions of trace cation activator elements such as  $Mn^{2+}$  and  $Fe^{3+}$  and rare earth elements such as  $Eu^{3+}$ ,  $Sm^{3+}$  and  $Dy^{3+}$  can affect the CL properties of minerals (Miller 1988). Some elements, quencher minerals, reduce the luminescence intensity (Budd et al. 2000).

Detrital quartz is derived from igneous or metamorphic provinces, and were subjected to high temperatures and pressures. Thus, crystal lattices experienced considerable defects and imperfections, which are responsible for detectable CL intensities (Owen 1991). Contrarily, temperature and pressure are less prominent during authigenic quartz cement precipitation, and lower concentrations of trace elements and lattice imperfections reduce the CL intensity to non-luminescence.

In this study, cathodoluminescence images have been quantified by image pointcounting. All CL photographing in this project has been done by using a cold cathode CL machine at 20kV/500mA, using 3200ASA-colour slide film, at exposure times of 6-9 minutes.

### X-ray diffraction (XRD)

Five samples were selected for determination of the bulk mineralogical composition by powder X-ray diffraction (XRD). Two samples were used for bulk XRD analysis (randomly oriented powder samples), five were used for identification of the clay fraction minerals of the detrital matrix and the authigenic clay, using oriented samples of <2 micron fraction. Samples were crushed manually to a sufficiently fine powder using an agate mortar and pestle. 1.5g of the sample was mixed with 5ml distilled water and these samples were ultrasonically treated for 10 minutes. The clay-sized fraction was separated by gravity settling (separation of the size fraction after 2 minutes of sedimentation). The separated fraction was smeared on glass slides and left to dry at room temperature. Four X-ray runs were made for each sample, to avoid the problems of XRD-peak overlap. The runs included air-dried samples (dried at room temperature), samples saturated with ethylene glycol (exposing the samples to ethylene vapour), samples heated to 490°C for 2 hours, and samples heated to 550°C for 2 hours, all to avoid the problems of overlapping XRD-peaks.

## Chemical analysis (atomic absorption spectrophotometry)

Variation in the bulk chemical composition of the rocks can give a good estimate about mineralogy and diagenetic evolution of the reservoir rocks in question. Chemical analyses were carried out on all seventeen samples. Major element concentrations (K, Na, Al, and Ca) were determined by atomic absorption spectrophotometry (AAS). The samples were crushed to powder with mechanical mortar then dried. 0.2 gm of each sample (rock powder) were mixed with 1g lithium borate and 0.4g boric acid in a platinum pot. The mixtures were heated on a flame or at least one hour. Then 5ml cesium chloride and lanthanum chloride solution were mixed with 5ml HNO<sub>3</sub> and heated. When the mixture in the platinum pot (rock powder) was completely dissolved, it was added to the cesium chloride and lanthanum chloride solution, and a HNO<sub>3</sub> mixture, and diluted to 100ml with distilled water. AAS depends on electron transitions between distinct energy levels within the electron shells of the atoms in the solution in question. Each specific element will absorb light at a distinctive (characteristic) set of wavelengths which its energies precisely match the differences between the energy levels involved in the transition. Light is supplied from a cathode hollow lamp with precise wavelengths and our sample (solution) is atomised by the flame and the machine measures the reduction in the intensity (absorbency) of the characteristic spectrum (wavelength) if the atoms are of the same element.

The samples were calibrated to standards with known concentrations of the element. A range of standard solutions (five) was made with different concentrations; absorbencies were measured and a linear correlation was calculated. The best fit between standard concentrations and absorption rates must be linear according to Beer's law (the absorption is proportional to the concentration of the free atoms in the vapour) but at higher concentrations it may be a curve. Blank solutions were also run and the average value of it (blank solution) were subtracted from the measured values. By applying the equation (x stands for a reading from atomic absorption measurement) the element concentrations were calculated. This number was multiplied by the dilution factor in order to obtain element concentration in the solution.

$$K_2O\% = ((\mu\text{g/ml} * \text{dilute factor}) / \text{sample weight}) * \text{total volume } 100\text{ml} * 1/10000$$

As we are interested in concentrations in the rock sample the value has to be corrected for the sample weight by applying the equation above. Two samples were analysed for each rock sample and the results were averaged.

## Back scattered electron imaging (BSE)

Small particles need to be examined carefully as they can have large impact on reservoir quality because of their very large specific surfaces. The chemistry, mode of occurrence and quantity of such components are of crucial importance in studying reservoir quality (porosity and permeability). The principles, techniques, and applications of scanning electron microscopy using back scattered electron imaging (BSE) is explained by Ruzyla (1986), Trewin (1988) and Evans et al. (1994). In simple terms, BSE images give in grey values a density map in terms of atomic number contrasts. Thus, due to low atomic number of the impregnation epoxy, the pores of the examined samples will appear black (Bloch 1994a). Depending on this principle, the method readily distinguishes for instance quartz and feldspar grains. Due to different atomic weights, the feldspar grains will show up as lighter grains and can easily be recognised. Some advanced machines can combine SEM-BSE, CL, Energy Dispersive X-ray analysis system (EDS) and the system can also be combined with image analysis programs for processing and quick results (Trewin 1988). EDS is a procedure in which carbon coated samples are bombarded with electron beams. This produces an X-ray spectrum characteristic of the elements present in the selected (focused) area (mineral) of interest. The results can be operated and further processed on a TV screen. EDS is providing good, quick qualitative or quantitative analysis at selected spots as small as 1µm diameter, allowing to identify the composition in terms type of feldspar (plagioclase, K-feldspar) and the general type of clay mineral (illite or kaolinite). In this study several spot analyses in feldspar and clay minerals were analysed by EDS to back up the results quoted from conventional petrography.

## Quantitative image analysis

Back scattered electron images (SEM) were used for porosity and permeability quantification due to high contrasts between solid material and porosity. Several samples were analysed by the program 'Image Tool' by digitising a number of SEM images. When necessary, the contrast in the images were enhanced by Adobe Photoshop. The images were converted to binary ones. The black colour is representing the pores and white is the solid grains plus cement and matrix. The amount of black (porosity) and white (minerals) pixels were quantified by the Image Tool

program. Results were compared with porosity values obtained by Helium porosimetry and thin section point-counting. However, the microporosity, which is present in the clay matrix and in the authigenic kaolinite, is not taken into account during thin section counting or in the SEM micrographs (using relatively low magnification). A disadvantage of the SEM is that quartz cement cannot be distinguished from the detrital quartz grains. The Kozeny-Karman equation can be applied in order to estimate the permeability and the enhanced binary image gives a unique opportunity to study the pore geometry, shape, size and tortuosity etc. A modified equation of well known Kozeny-Karman equation was used (Mowers and Budd 1996). The equation is written as:

$$K = \Phi^3 / c(1 - \Phi)^2 (4PP / \pi PA)$$

Where, K is permeability, PP is pore perimeter, PA is pore are and  $\phi$  is porosity. All these parameters are obtainable by image analysis. Using the Image Tool software, one can calibrate the measurements from pixel units to micrometers by measuring an object with known length (the scale bar). Images obtained by CL are expected to show greater amounts of image porosity as the quartz overgrowths (non luminescent) will not be counted for as solid material (under-estimated). This method is expected to give an impression about the effect of quartz overgrowths on petrophysical properties (porosity-permeability). Mean grain size and rounding can also be estimated using image analysis. CL measurements are expected to show finer quartz grain size values and better rounded grains in contrast to transmitted polarised light images (due to the effects of the presence of syntaxial authigenic quartz overgrowths).

## Results

### Petrophysical measurements

The results of the porosity and permeability measurements are shown in Tables 2 and 3. The sandstones have a high porosity, with a narrow range of 21.4 B 27.5% (averaging 23.8%; N=14), and a high permeability (range 345.9-2468.3mD, averaging 1350.6mD; N=12). The reservoir properties are thus very good. Vertical and horizontal permeability do not show any significant difference. The sandstones have good reservoir quality with high (economic) porosity and permeability values. Porosity and permeability have a positive correlation (R = 0.484; N = 12). A cross plot of these two parameters is shown in Figure 3.

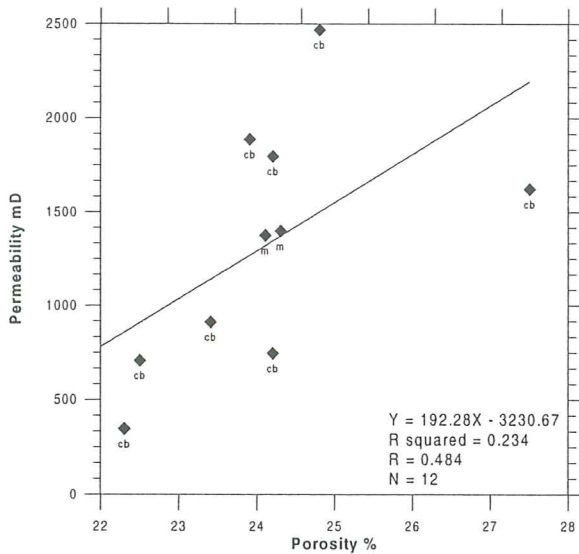


Fig. 3: Plot of porosity versus permeability values showing a statistically significant positive correlation between the two variables. The samples do not show much variability in porosity (ranging from 21.4 to 27.5%), although the permeability values do change considerably (ranging from 345.9 to 2494.4mD). The figure also shows that the main facies (massive and cross bedded sandstones, labelled with 'm' and 'cb', respectively) have similar properties.

Table 2: Results of porosity measurements (%), with mean values and standard deviation.

Sample Name	Helium porosity measurements %					Standard Deviation	Mean Porosity %	Mean grain density
	1	2	3	4	5			
B	24.6	22.5				1.5	23.5	2.64
G1	24.3					-	24.3	2.64
G2	22.2	24.7	25.3			1.6	24.1	2.64
G4	24.7	23.5	24.1	24.5		0.5	24.2	2.64
G5						-	--	--
G6	21.3	22.5	23.2	22.6	27.5	0.8	23.4	2.64
G7	22.3	22.6	22.2	22.1		0.2	22.3	2.64
G8	21.9	24.0	21.5	22.7		1.1	22.5	2.64
G27	23.8	25.8				1.4	24.8	2.64
G28	23.9					-	23.9	2.64
G29	24.8	23.6	24.5	24.1		0.5	24.2	2.64
G30	27.5					-	27.5	--
G31	19.7	19.7	25.3	22.0	20.1	2.4	21.4	2.64
G32						-	--	--
G33T	23.3					-	23.3	2.64
G33	23.9					-	23.9	2.64

Table 3: Results of the permeability measurements of plugs taken parallel to the bedding (horizontal permeability) and in a direction perpendicular to the bedding surfaces (vertical permeability). When sub-samples were available, more measurements have been performed. In two cases of aberrantly low values (due to a nearly impermeable clay laminae in the plug), marked with an asterisk (\*), these measurements were not used for the average value.

Sample	Horizontal Permeability (mD) 1	Horizontal Permeability (mD) 2	Vertical Permeability (mD) 1	Vertical Permeability (mD) 2	Average Permeability (mD)	Sandstone Facies
B					--	--
G1			1398.0		1398.0	Massive
G2			1375.6		1375.6	Massive
G4	748.3	741.6	113.3*	95.6*	744.9	Cross bedded
G5					--	Cross bedded
G6			911.2		911.2	Cross bedded
G7			345.9		345.9	Cross bedded
G8		703.8	737.8	679.5	707.1	Cross bedded
G27			2494.4	2442.3	2468.3	Cross bedded
G28			1887.3		1887.3	Cross bedded
G-29	1612.0	1980.9			1796.4	Cross bedded
G30	1309.2	1934.9			1622.0	Cross bedded
G31	1291.7		1032.3		1162.0	Cross bedded
G32					--	Flaser bedded
G33t					--	Massive
G33			1788.0		1788.0	Massive
B					--	--

## Petrographic analyses

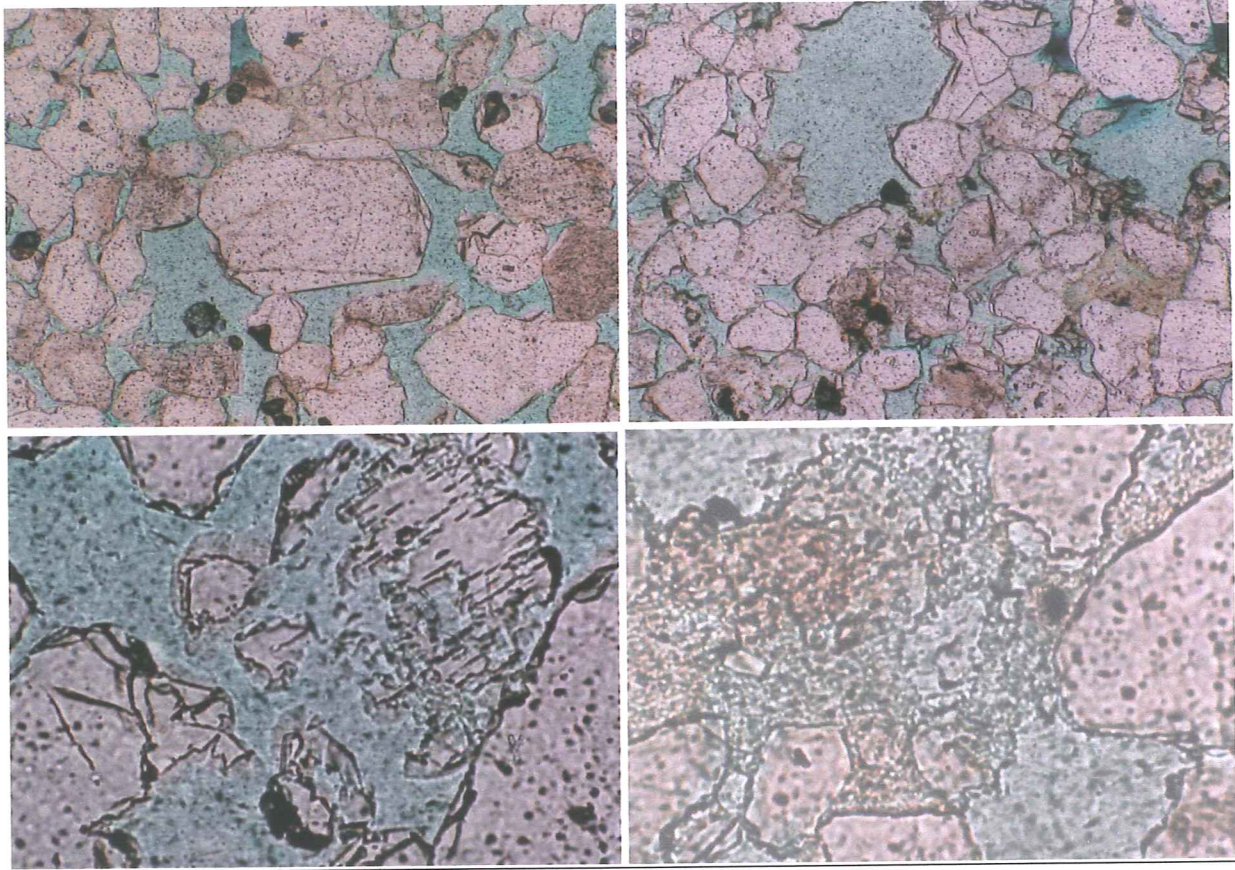
The results of the thin section point counting are shown in the Table 4. The purpose behind point counting different quartz grain types (monocrystalline quartz, undulous monocrystalline quartz and polycrystalline quartz) is to test the susceptibility of quartz cement nucleation for each of these grain types. Feldspar content, secondary pores, matrix and authigenic clay content are important parameters which can effect petrophysical properties (porosity and permeability).

Table 4: The results of thin section point counting of detrital and diagenetic components.

Sample name	Unstrained mono-crystalline quartz	Strained mono-crystalline quartz	Poly-crystalline quartz	K-feldspar	Clay minerals (kaolinite)	Other matrix	Quartz overgrowth cement	Rock fragments	Primary pores	Secondary pores	Total pores
B	35.3	13.0	6.6	2.0	3.0	3.0	13.3	0.0	14.3	9.3	23.6
G1	34.6	12.3	10.0	0.6	0.3	0.0	12.0	0.6	16.3	13.0	29.3
G2	51.6	13.0	5.6	2.6	0.3	0.6	3.6	0.6	9.3	12.3	21.6
G4	45.3	12.3	4.3	1.0	2.6	1.6	6.0	1.0	12.3	13.3	25.6
G5	48.6	6.3	2.6	2.6	4.0	5.0	7.0	3.3	6.6	13.6	20.2
G6	44.6	9.6	4.6	2.6	2.6	0.3	7.0	1.0	9.0	18.3	27.3
G7	56.0	8.0	4.3	3.6	5.6	2.0	2.6	1.3	6.6	9.6	16.2
G8	48.0	8.3	4.0	2.0	4.3	3.3	5.6	1.0	4.0	19.3	23.3
G27	43.6	13.3	8.3	2.3	2.0	1.6	3.6	2.0	9.0	14.0	23.0
G28	36.3	15.3	8.0	2.3	2.0	0.6	7.6	1.3	8.6	17.6	26.2
G-29	44.0	8.3	5.3	2.3	2.0	2.3	8.6	1.0	4.3	21.3	25.6
G30	46.6	9.3	7.0	2.3	1.0	1.0	2.3	2.0	8.3	20.0	28.3
G31	-	-	-	-	-	-	-	-	-	-	-
G32	43.0	14.3	9.6	2.0	3.6	2.6	8.3	0.3	7.3	8.6	15.9
G33t	44.0	10.0	7.3	3.3	3.0	1.0	8.0	1.3	7.6	14.3	21.9
G33	-	-	-	-	-	-	-	-	-	-	-
B	-	-	-	-	-	-	-	-	-	-	-

### Detrital components

The Bentheim sandstones are mainly composed of quartz grains, with few K-feldspars and some rock fragments. Point counting shows that the Bentheim sandstones predominantly are quartz arenites to subarkoses (average composition is  $Q_{94.7}F_{3.4}L_{1.8}$ ). Quartz grains are unstrained monocrystalline quartz (35-56%), strained (undulous) monocrystalline quartz (6-15%), and polycrystalline quartz (3-10%). The random orientation of undulosity patterns suggests that it is inherited from the source rock, not from compactional grain deformation within the sandstone. K-feldspar with well-developed cleavage and some twinning is the dominant feldspar type (1-4%). Some grains clearly show microcline type twinning. Most grains are elongated and angular due to breakage during sedimentary transport, along the cleavage planes. Additional angularity is caused by dissolution along the grain margins which often appear ragged. Only traces of plagioclase feldspar have been observed. Most feldspar grains show dissolution preferentially along the cleavage planes and twin boundaries. Lithic grains (0-3%) are mainly composed of metamorphic rock fragments, siltstone, and chert or microcrystalline quartz grains. Detrital matrix is largely absent. However, detrital clay in the form of clay laminae, clay filled burrows and clay cutans is present in some samples. The clay cutans are only present in the two samples from the surface outcrop.



*Fig. 4: Polarised-light micrographs showing quartz cement, partly dissolved K-feldspar and oversized pores (completely dissolved feldspar), and authigenic kaolinite. A.. Example of a thick and well-developed (euhedral) quartz overgrowth on a elongated detrital quartz grain. The overgrowths are recognisable because of a clear dust-rim. Open pores (blue colour; sample impregnated with blue stained resin) are partly reduced primary intergranular pores. B. Secondary porosity is a dominant phenomena in almost all samples. They were formed by dissolution of framework grains, such as plagioclase and K-feldspar grains. In most cases they significantly contribute to the bulk intergranular porosity. Two oversized pores (upper right and left to the figure), and some authigenic kaolinite is present in the lower left. C. A case of porosity enhancement by K-feldspar destruction by dissolution. The surrounding quartz grains have straight outlines evidencing presence of quartz cement overgrowths. D. The kaolinitisation of feldspar (dissolution of detrital feldspar followed by precipitation of kaolinite-dickite in the secondary pore). Microporosity is present in between the kaolinite booklets.*

#### *Authigenic components*

Authigenic quartz occurs as syntaxial overgrowths on detrital quartz grains (Fig. 4A). Overgrowths are difficult to recognise, because the dust-rims are absent or discontinuous. Overgrowths are best developed around monocrystalline quartz grains, less well around fine-crystalline quartz grains and absent around chert grains. It is clear in many cases that quartz overgrowth were growing into the pre-existed secondary pores and sufficient space due to oversized pores provided sites for euhedral growth of quartz overgrowths (Harwood 1988). In may cases a dissolved feldspar grain is surrounded by quartz overgrowths probably indicating that silica released through this dissolution was used up (consumed) through this kind of cementation (Fig. 4C). Thus, quartz cementation was probably taken place after feldspar dissolutions or at least must have been simultaneously. Authigenic clay in the form of well-developed, randomly oriented kaolinite booklets which are pore filling is present in small quantities in most samples. This kaolinite fills large pores which must have been secondary pores by dissolution of former detrital grains (Fig. 4D).

### Pores

Three types of pores can be distinguished in the Bentheim sandstones: reduced intergranular pores, moldic pores (oversized pores) and micropores. The intergranular porosity is considered to be the depositional porosity, although it has been reduced by the quartz cement. The primary pores of these sandstones are partly filled by quartz cement, and partly with detrital clay (illite) probably through bioturbation and mechanical infiltration. Secondary pores are present in all samples (Fig. 4B). These are easily recognisable, because they are commonly larger than the mean grains and in many cases traces of remaining feldspar (partly dissolved K-feldspars) are still present. In addition, some of these pores have an elongated angular form, similar in form to the K-feldspar grains which survived dissolution. Part of these pores is filled by authigenic kaolinite. Micropores are present in between the pore filling kaolinite booklets and occurs in partly dissolved K-feldspar grains.

### Backscatter images

Scanning electron micrographs, using back scattered electron imaging, provided useful information about important features such as secondary porosity (Fig. 5). The high contrast in the images between quartz and feldspar grains and pores enabled reliable qualitative and also quantitative analyses of the feldspar content. Typical features were selected to demonstrate petrographical relationships. Fig. 5A shows reduced primary intergranular porosity (black) and some oversized pores at least the same size as detrital grains, in the central part of the image. Most of the grains (dark grey) are quartz, the straight boundaries indicate the presence of syntaxial quartz overgrowths. The light grey grains are K-feldspars. This images gives an impression that feldspars are significantly less abundant than quartz grains, which supports point counting results. Besides dissolved feldspar grains and oversized pores (secondary porosity) in the middle of the image, some indications of feldspar dissolution can be seen. In Fig. 5B a partly dissolved K-feldspar grain (light grey) is shown. It has ragged outlines and extensive microporosity within the grain as caused by dissolution preferentially attacking along the cleavage planes in the feldspar crystal. Fig. 5C is similar to 5B, but the former image shows less porosity because of more extensive quartz cementation, as indicated by the close packing and straight margins of many quartz grains (dark grey).

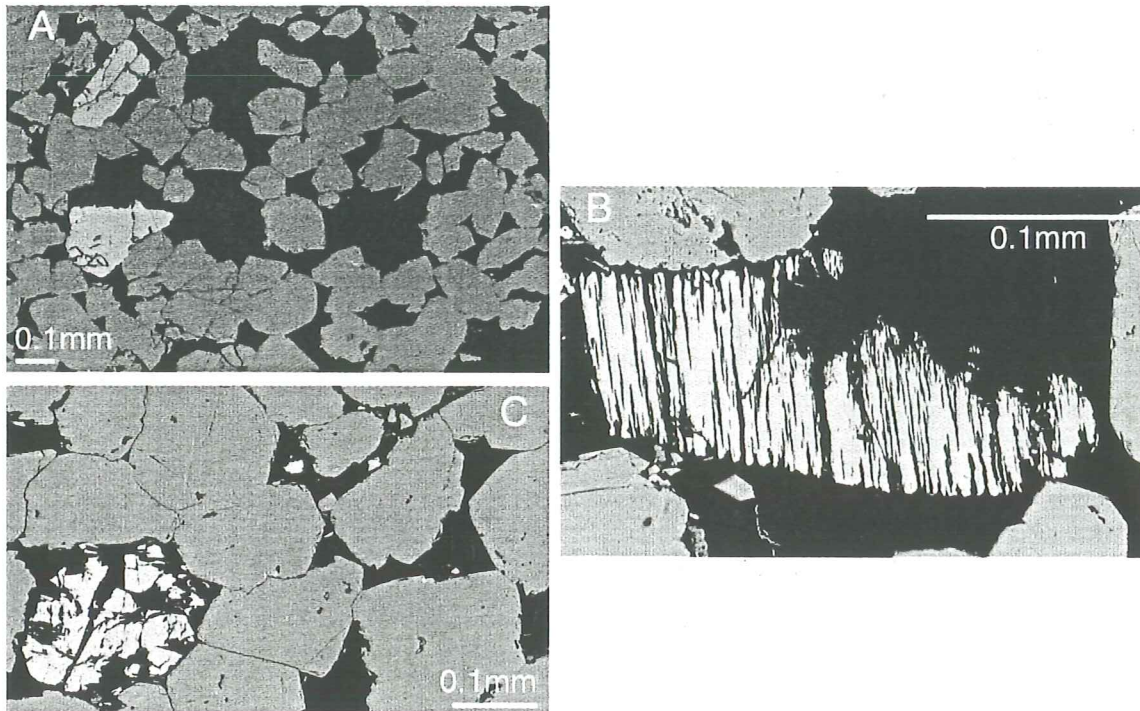


Fig. 5: SEM back scatter electron photomicrographs.

## Cathodoluminescence microscopy

The presence of quartz cement in the form of overgrowths is more visible using CL techniques than with conventional petrography, using the standard criteria for discriminating between detrital quartz and quartz overgrowths. Generally the distribution of quartz overgrowth cements is uneven and not characterised by a specified pattern, i.e., randomly distributed in shape and quantity. The thickness of the overgrowths is highly variable between different grains and samples. The reason for this variation in quantity and distribution pattern is not clear. In some samples the euhedral boundaries are perfectly developed (which straight lined boundaries) in other samples the cement apparently has irregular boundaries. Some examples are shown in Figure 7 displaying both transmitted polarised light and CL images. Such paired images can together reveal much information which is needed for good thin section analysis and quantification.

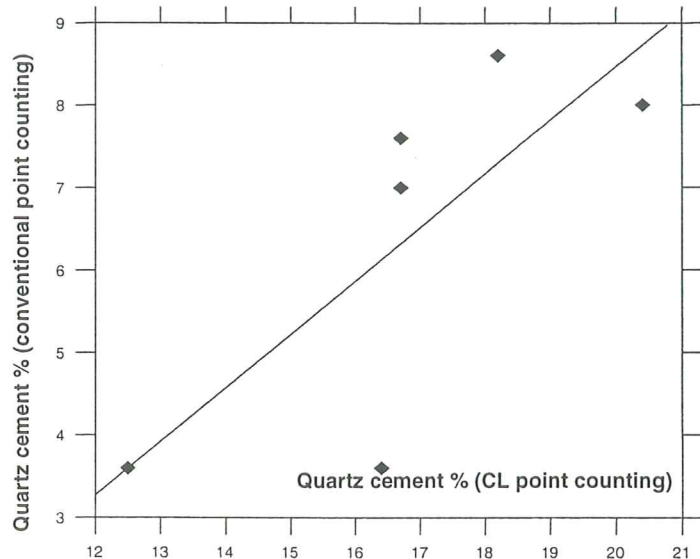
The main components (quartz overgrowths, detrital feldspar and quartz grains, quartz overgrowths, and porosity) have been quantified using point counting (along a grid) of CL images. The results are given in Table 5 and are compared with the quantitative results obtained with helium porosity and conventional thin section point counting.

Table 5: CL image point counting results.

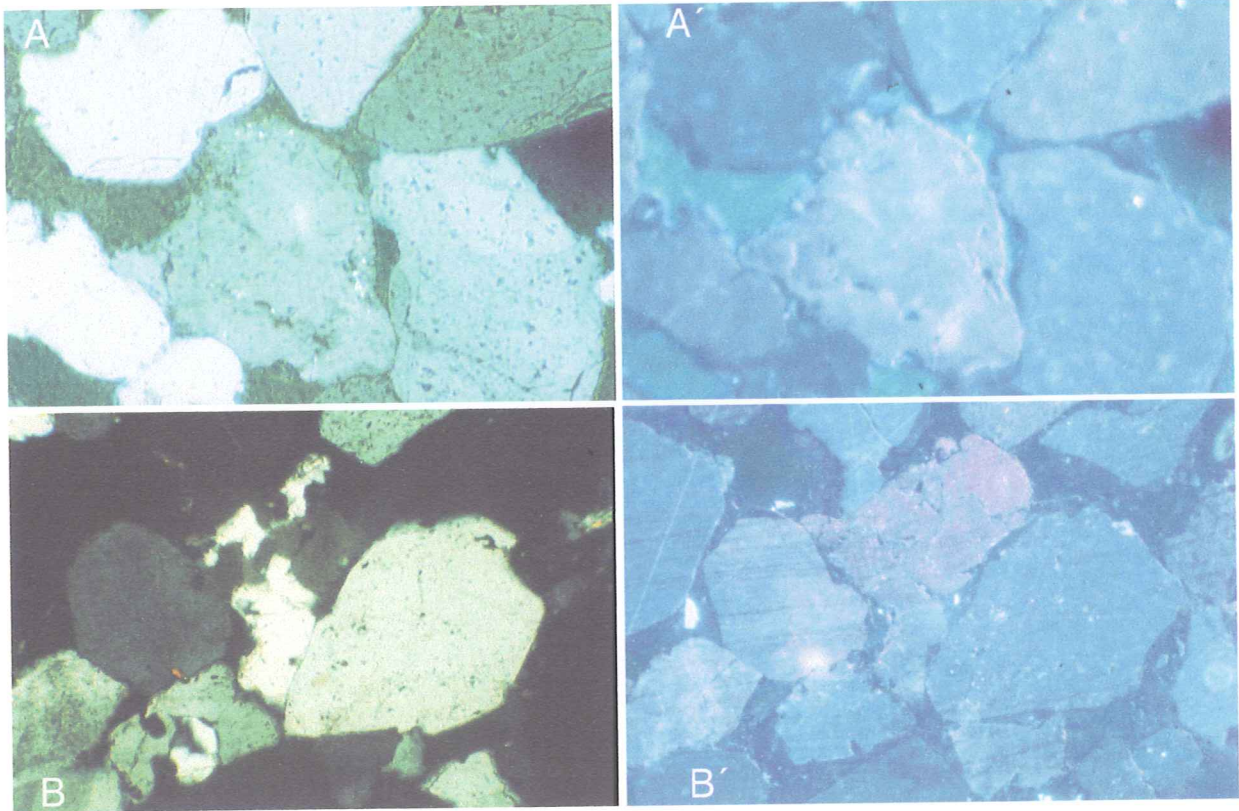
Samples	Quartz overgrowth %	Feldspar %	Detrital Quartz %	CL Porosity %	Helium Porosity %
G2	12.5	12.5	48.0	28.9	24.1
G27	16.4	5.4	52.7	25.4	24.8
G28	16.7	3.7	51.8	27.8	23.9
G29	18.2	5.4	47.3	29.1	24.2
G33	20.4	7.4	44.4	27.8	23.3
G6	16.7	14.8	26.0	20.4	23.4

Only 6 samples could be quantified due to technical limitations. For reasonable results the number of counts was about 100, which is too few but it was hoped that we can get at least an idea about the correlation between transmitted light petrography and CL petrography. CL point counting was done by putting a regular rectangular grid over selected CL pictures (around 50 points were counted). As was expected, by using conventional petrography the significance of quartz overgrowth is underestimated (Fig. 6). Therefore it is important in future research to combine CL as an integrated part of any attempt to assess the reservoir quality, in particular the effect of quartz overgrowths. Porosity is overestimated in CL images due to the difficulty in distinguishing between matrix and clay which also has a blue CL colour.

Fig. 6: A comparison between the percentages quartz cement obtained by pointcounting CL images and standard polarised lightpoint counting. The correlation is positive and significant ( $R = 0.755$ ;  $N = 6$ ). It is evident that quartz cement (overgrowths) as estimated by polarised light microscopy point counting is significantly underestimated and thus inaccurate. This can be explained by the fact that dust rims, marking the detrital quartz grains from the syntaxial overgrowths, are not always completely developed, making the distinction between grains and cement difficult and arbitrary.







*Fig. 7: On the right the CL image, on the left the crossed-polar polarised light images. The CL image enables to distinguish bright blue detrital quartz, quartz overgrowths (dark blue luminescent) and pore space (non-luminescent). These images illustrate that grains without euhedral boundaries and dust rims have substantial quartz cement overgrowths. The primary intergranular porosity has thus been reduced by the quartz cement.*

## Correlations

### *Kaolinite vs permeability and porosity*

The helium porosity and the gas permeability values plotted against the percentages authigenic kaolinite (obtained by thin section point-counting). It is evident that both porosity and permeability are significantly affected by the presence of authigenic kaolinite, both parameters decreasing with increasing amount of authigenic kaolinite (Fig. 8).

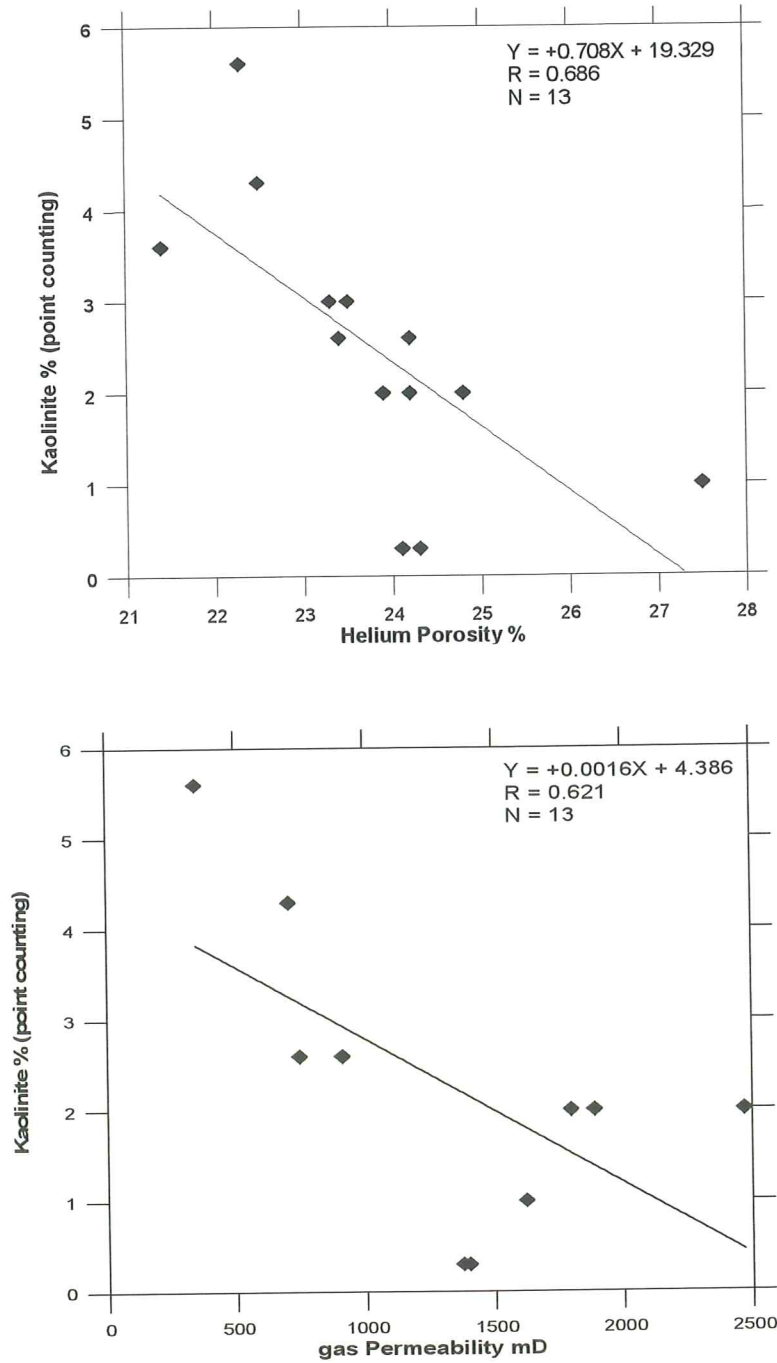
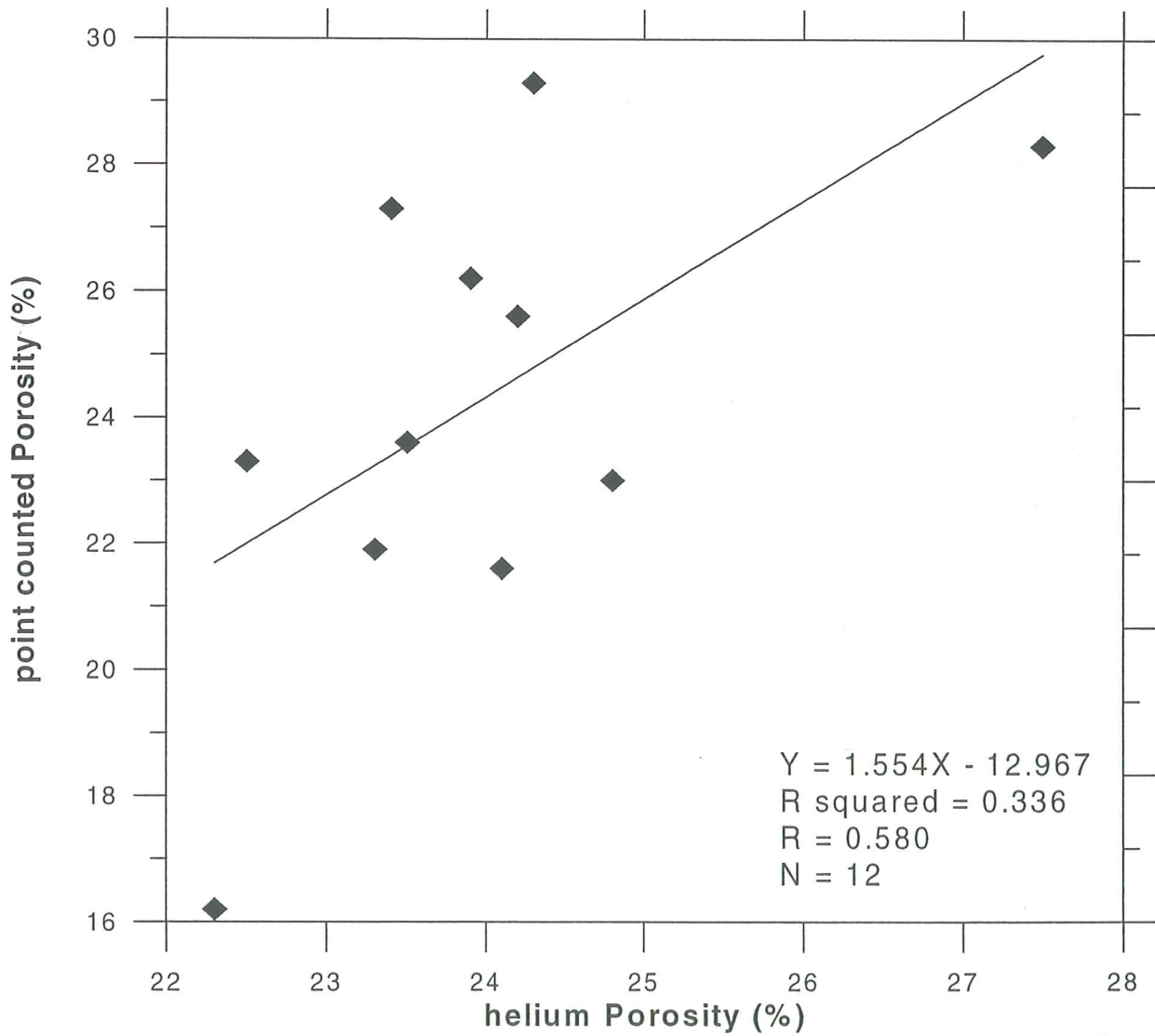


Fig. 8: Kaolinite versus permeability and porosity.

*Porosity-porosity*

Point-counted porosity versus Helium porosity (Fig. 9) show that the two different methods for porosity measurement do not correlate. The correlation coefficient indicates lack of significant correlation. Low point-counting values could be the effect of the microporosity in the kaolinite-filled pores and in the partly dissolved feldspar grains which is counted for by Helium porosity measurements in contrast to conventional thin section point counting.



*Fig. 9: porosity crossplot.*

*Quartz substrate vs quartz cementation*

Quartz overgrowths are not more abundant in sandstones enriched in monocrystalline quartz grains, as was expected (Fig. 10). This may well be caused by the biased (inconsistent) results from point counting. However, the CL images indicate that quartz cement is less abundant on microcrystalline quartz grains.

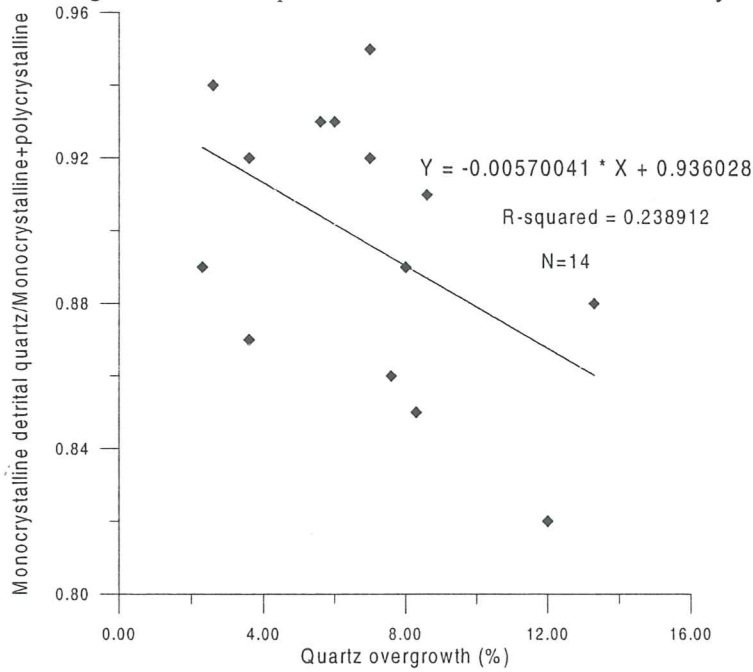


Fig. 10: Quartz substrate vs quartz cementation.

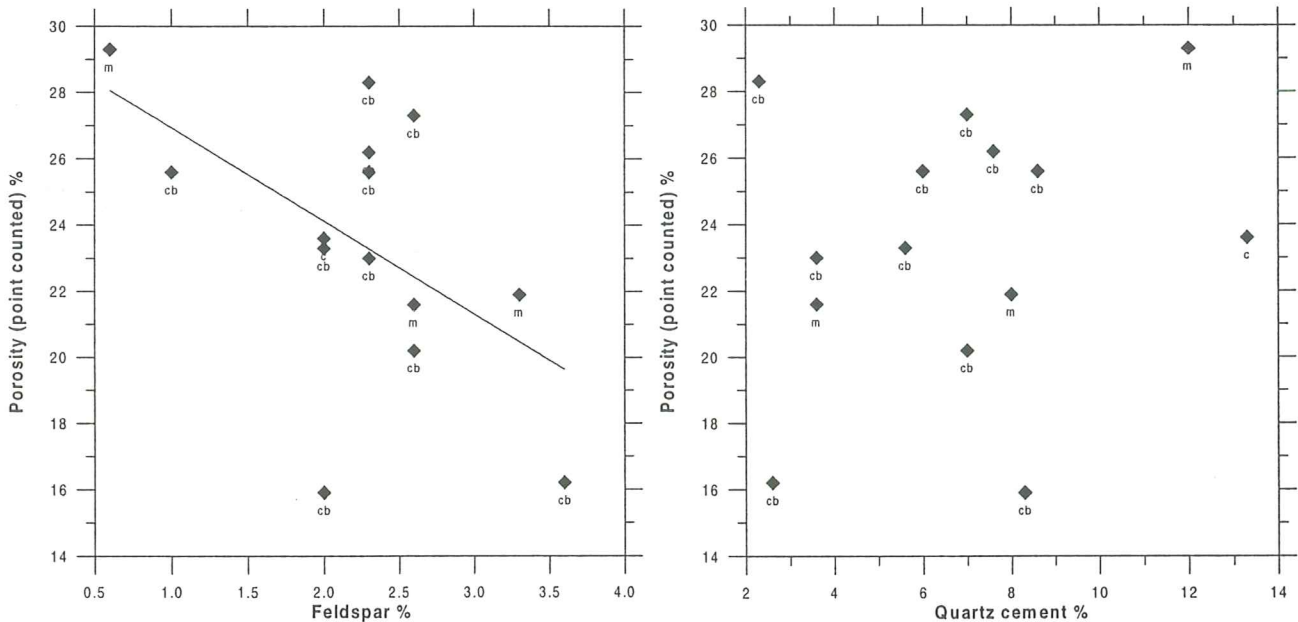


Fig. 11: Crossplots for porosity, feldspar and quartz cement.

*Porosity versus feldspars and quartz cement*

The lack of significant correlation (R = 0.226; N = 14) between quartz cement and porosity (Fig. 11) could be due to the significant role of feldspar dissolution and secondary porosity on the sandstone properties (the correlation between feldspar and porosity is significant: R = 0.534; N = 14). However, it is possibly that the inconsistency of the point counting method and the difficulty in recognising quartz overgrowths resulted in severe underestimation of the percentage of quartz cement.

**Quantitative image analysis of backscatter images**

The contrast between grains (feldspar and quartz) and the porosity in back scatter electron images are high which allows quantification of porosity and permeability using image analysis software. The results of the image analysis were compared to the standard helium porosity and permeability values (Table 6). The results of both techniques are comparable, pointing to the reliability of the image analysis method (Fig. 12). Porosity values by both methods seem to correlate better than the permeability values do. This is probably due to two factors. Firstly, the Kozeny-Karman equation, used for calculating permeability from the image analysis, has a constant which is evidently not consistent for all types of lithology and thus has to be adapted if one wants to get better results (a trial and error method could be used trying different numbers until a reasonable correlation is achieved). Secondly, the permeability is much more sensitive than porosity as it is a complex function of many parameters, among others, pore geometry, specific surface, grain size etc., and a small under- or over-estimation of one variable will cause significant variation of the results. The Kozeny-Carman equation combines three important parameters (Porosity  $\Phi$ , Specific surface  $ss$ , and pore tortuosity  $L_e / L$ ) in order to account for permeability according to the equation below:

$$K = \theta^3 / K_o (L_e / L)^2 (1 - \theta)^2 ss^2$$

Where  $K_o$  is the Kozeny constant. For use with thin section data, the two dimensional expression for specific surface must be substituted, and a proportionality constant,  $c$ , can be substituted for  $K_o (L_e / L)^2$  (cf. Mowers and Budd 1996). The equation is then re-written as:

$$K = \theta^3 / c (1 - \theta)^2 (4pp/\pi PA)^2 \text{ (cf. Mowers and Budd 1996),}$$

where PP is pore perimeter and PA is pore area and  $c$  was assumed to be 5. Fortunately these parameters, e.g. the pore perimeters (PP), porosity ( $\Phi$ ) and pore area (PA) are automatically quantified by the Image Analysis software, provided that the images are in binary format. Automatic threshold was used for all samples. The software automatically analyses all the objects (pore perimeter and pore area) within the image and takes the mean value of all analysed objects. The results of PA and PP for the measured samples are shown in Table 6. It is always possible to enhance the accuracy (to get results close to laboratory measurements) by modifying the thresholds of binary images and by slightly changing the constant  $c$ . Only slight changes of estimated PA and PP results in significant permeability variations. Thus, one can gain an idea about the sensitivity of permeability to the factors which control it.

*Table 6: Comparison of values of main petrophysical properties obtained by using both standard techniques and image analysis (IA) of SEM micrographs. Pore areas and perimeters were calculated with image analysis.*

Samples	PA ( $\mu\text{m}^2$ )	PP( $\mu\text{m}$ )	Porosity (IA) %	Helium Porosity %	Permeability (IA) (mD)	Gas permeability (mD)
G1	2899.20	208.47	24.1	23.5	470.1	1398.0
G29	4013.66	260.76	23.9	24.2	864.2	1796.4
G30	880.12	56.30	29.7	27.5	1153.0	1622.0
G32a	385.19	29.13	19.2	-	491.1	
G4a	2400.85	160.75	20.3	24.2	707.4	744.9
G6	1575.28	159.45	19.8	22.1	650.2	911.2
G8	2334.42	194.12	21.2	22.4	255.7	707.0
B	823.41	40.83	19.2	25.0	235.2	-

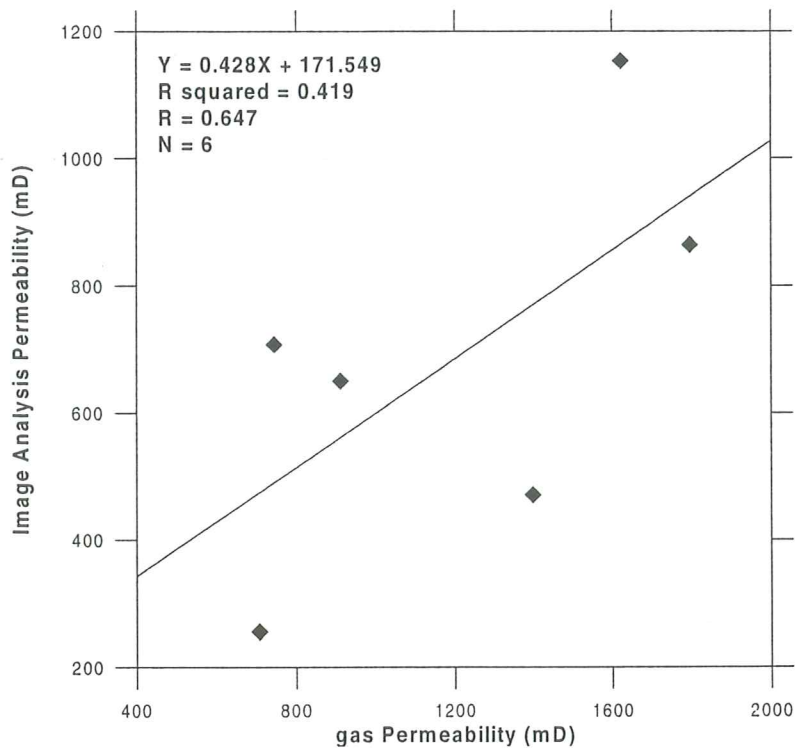
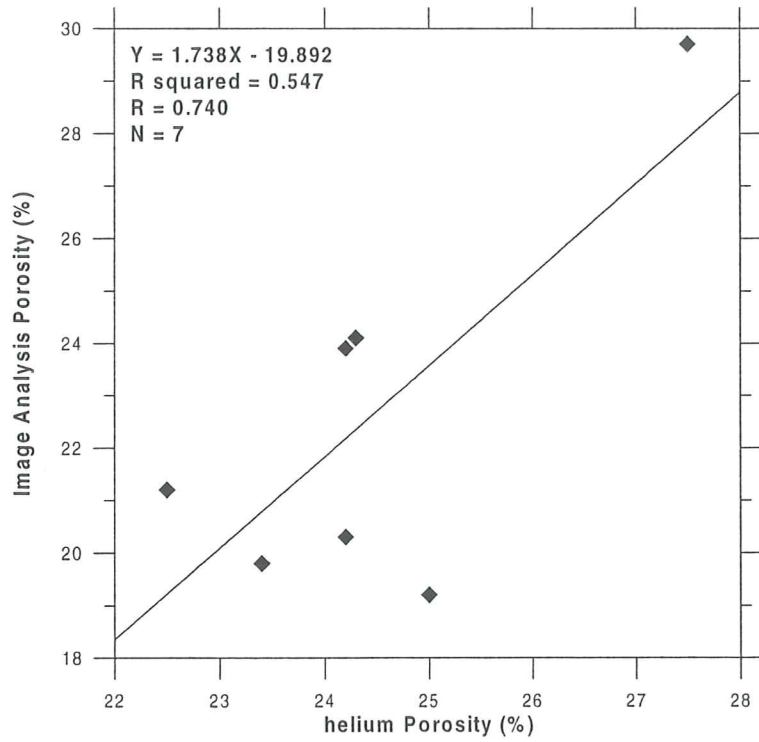


Fig. 12: The correlation between petrophysical measurements measured by image analysis and petrophysical measurements of porosity and permeability.

## Chemical composition

The results of the chemical analysis (AAS) are given in Table 8. The calcium contents of all sandstone samples are very low. The potassium concentrations confirm that K-feldspar is the main feldspar, but small amounts of Na-feldspar could also be present, or the Na could be admixed within the K-feldspar. Na and K correlate positively ( $R=0.666$ ;  $N=14$ , leaving out samples from the surface outcrop and the flaser bedded sandstone with a high clay content) suggesting that they are both mainly bound to feldspar. The high Al content of sample G32 is consistent with the fact that this sample is from a flaser bedded and bioturbated sandstone, rich in clay laminae and clay filled or lined burrows.

Table 8. The main element concentrations (measured by AAS), and the calculated feldspar and kaolinite percentages.

Sample	Al%	K%	Na %	Ca%	K-feldspar%	Na-feldspar %	Total Feldspar %	Kaolinite%
B	0.4946	0.0966	0.0301	0.0074	0.69	0.36	1.05	1.87
G1	0.5582	0.2463	0.0162	0.0065	1.75	0.19	1.95	1.76
G2	0.4962	0.2279	0.0099	0.0060	1.62	0.12	1.74	1.56
G4	0.8868	0.3357	0.0151	0.0070	2.39	0.18	2.57	3.05
G5	0.8469	0.3322	0.0137	0.0060	2.36	0.16	2.53	2.87
G6	0.4549	0.2313	0.0099	0.0050	1.65	0.12	1.76	1.35
G7	0.8619	0.3529	0.0145	0.0050	2.51	0.17	2.69	2.87
G8	0.9300	0.3304	0.0132	0.0055	2.35	0.16	2.51	3.28
G27	0.6105	0.2424	0.0092	0.0050	1.73	0.11	1.83	2.07
G28	0.5422	0.2214	0.0080	0.0055	1.58	0.09	1.67	1.82
G-29	0.6131	0.2783	0.0117	0.0071	1.98	0.14	2.12	1.95
G30	0.5873	0.2906	0.0097	0.0060	2.07	0.12	2.18	1.79
G31	0.4470	0.2806	0.0108	0.0075	2.00	0.13	2.13	1.15
G32	1.5135	0.5010	0.0145	0.0060	3.57	0.17	3.74	5.50
G33t	0.6325	0.2929	0.0095	0.0060	2.08	0.11	2.20	2.00
G33	0.4326	0.2276	0.0078	0.0058	1.62	0.09	1.71	1.27
B2	0.7734	0.1734	0.0101	0.0088	1.23	0.12	1.35	3.07

Fig. 13A shows a plot of Al against K %. B. Plot of Na against Al. Samples from the surface outcrop at Brochterbeck contain in addition to K-feldspar and authigenic kaolinite also detrital illite in the form of clay cutans (attributed to surface weathering in the outcrop). In Fig. 13C only samples from the Gildehaus quarry are included. Al and K show a significant positive correlation ( $R = 0.877$ ;  $N = 14$ ). K is contained only in K-feldspar, whereas Al is bound to both K- and Na-feldspar and authigenic kaolinite. Figure 13C and D show the correlation between feldspar and kaolinite calculated from AAS results and by thin section point counting. Assuming that all K and Na are bound to feldspar, the amount of feldspars and of kaolinite can be calculated (Table 8).

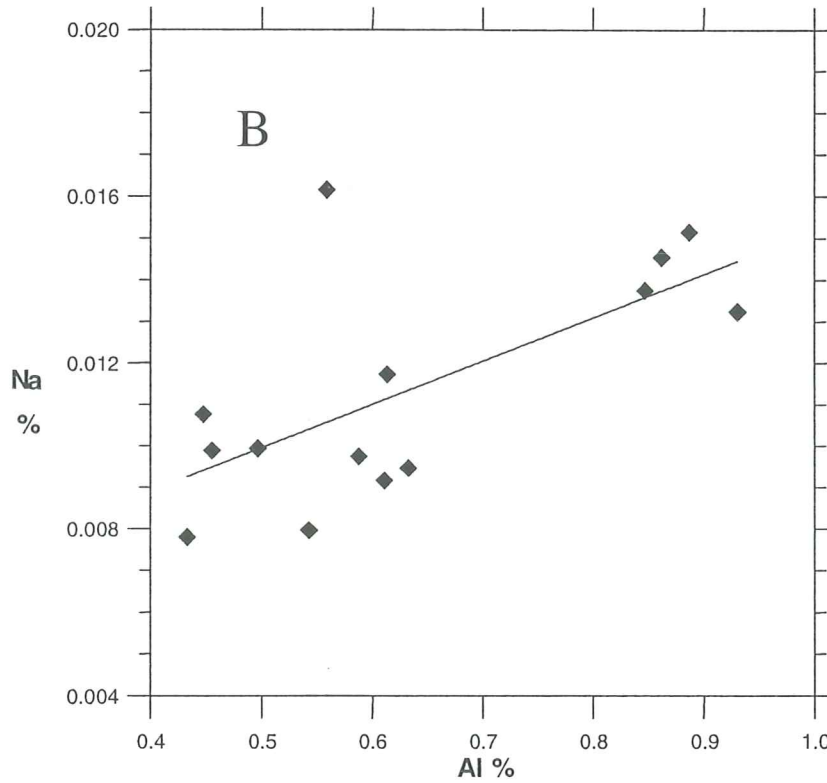
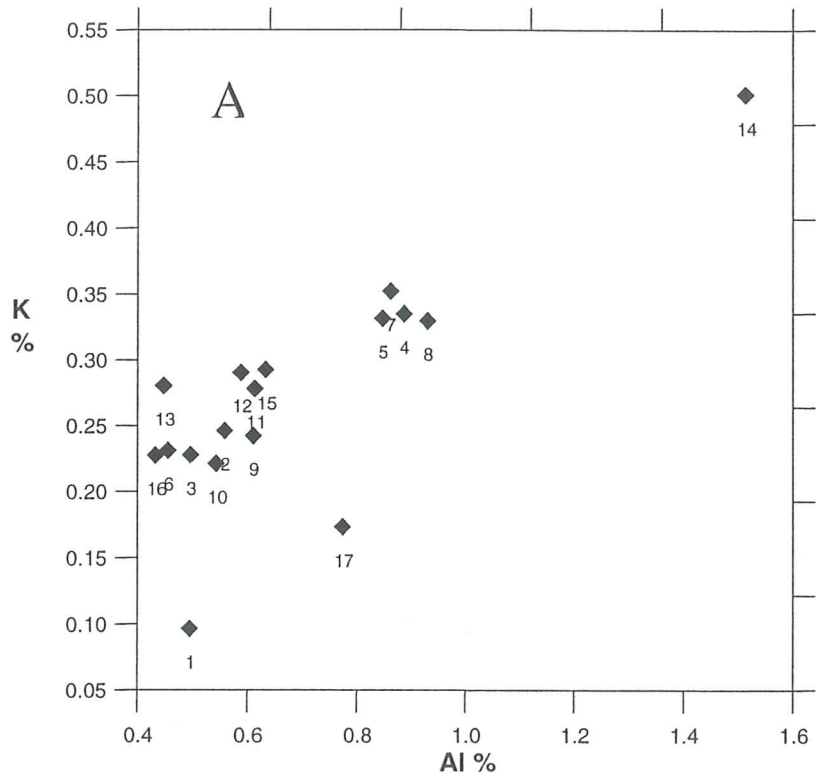


Fig. 13A and B: AAS element crossplots.



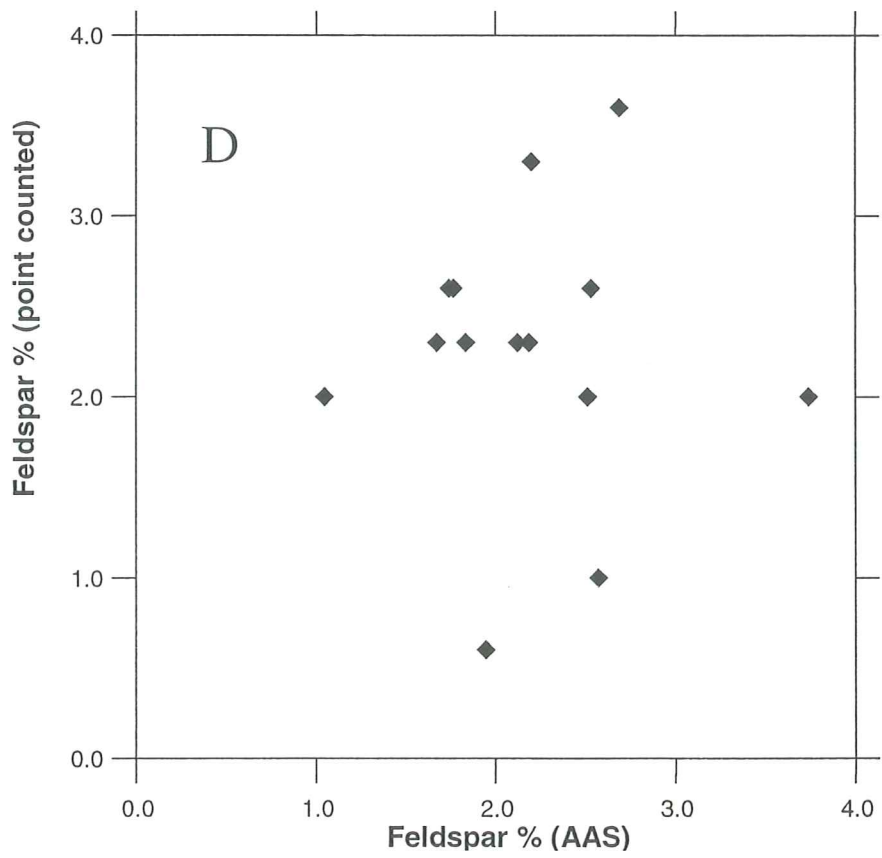
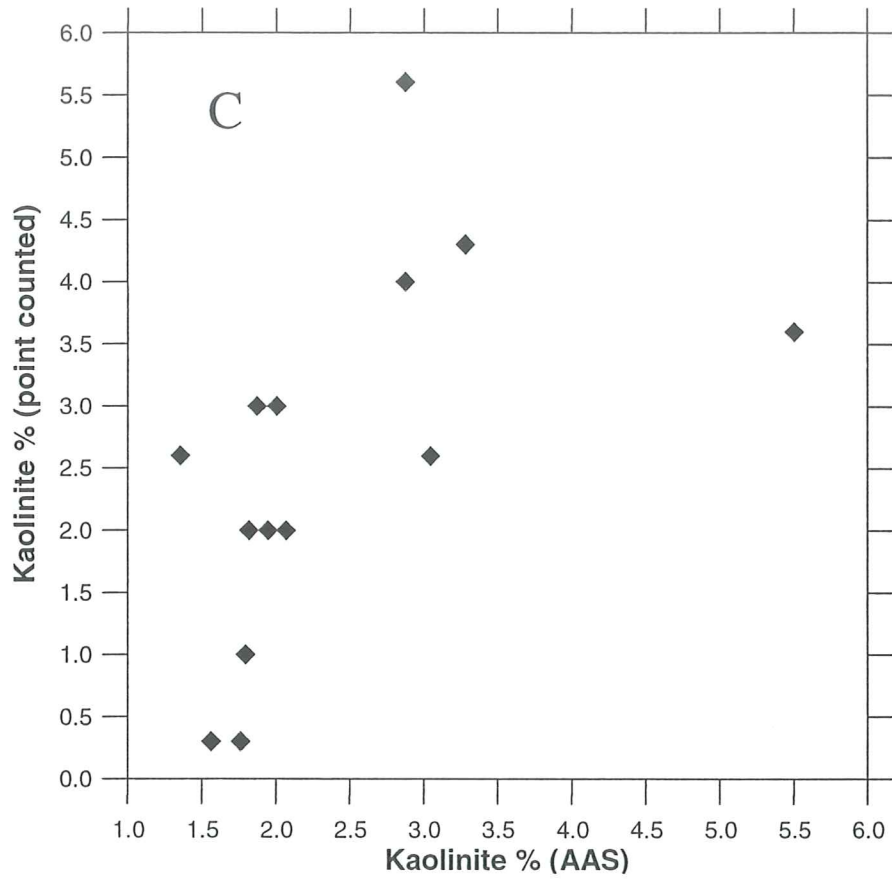


Fig. 13C and D: calculated mineral contents based on AAS and point-counting.

## XRD

The XRD analysis of 2 bulk and 5 oriented samples indicates the dominant presence of quartz and minor amounts of feldspar and clay minerals. The feldspars which can be identified in the Bentheim sandstones are mainly microcline. Clay minerals present are kaolinite and illite. From petrographic analysis it is evident that the kaolinite is authigenic (filling secondary pores) and the illite is detrital (bound to clay laminae, clay cutans and burrows). The fact that not all kaolinite did collapse up on heating, suggests that also dickite is present. Dickite is thermodynamically more stable than kaolinite (Worden and Morad 2000).

Table 9: Result from wholerock XRD analysis.

Samples	Quartz	Feldspar
G1	+++	-
G2	+++	+

Table 10: Results from XRD on oriented on the clay fraction samples.

Samples	Kaolinite	Illite
G1	+++	+
G2	+++	+
G7	+++	+
G28	+++	+
B	++	++

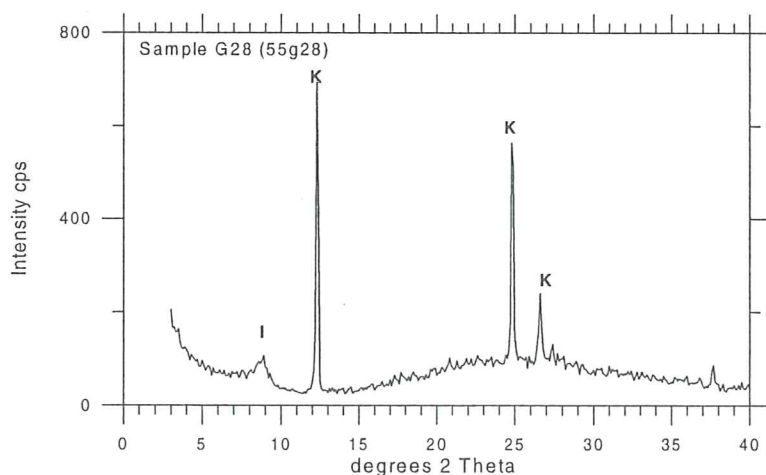


Fig. 14: Clay fraction XRD, air-dried sample, sample G28 for clay identification.

Identified minerals are kaolinite (K) and detrital illite (I).

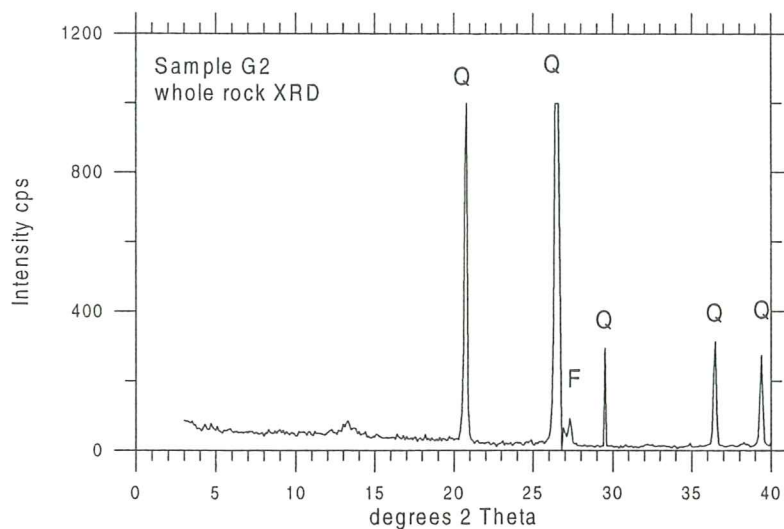


Fig. 15: Whole rock XRD analysis of sample G2 showing the main components of the sample: quartz (Q), K-feldspar (F), and clay minerals such as authigenic kaolinite (K) and detrital illite (I). As expected, quartz (Q) is the major component.

## Discussion on the diagenesis and reservoir characteristics of the Bentheim sandstones

Evidently the present-day quartz-rich composition of the Bentheim sandstones is partly of diagenetic origin. At the time of deposition the detrital composition was not the same, but instead it was more arkosic. This modification also affected the petrophysical properties. This argument is verified by the abundance of oversized pores and the presence of partly dissolved feldspar grains. The original feldspar grains were partly or completely dissolved, taking into account that the oversized pores represent dissolved detrital feldspar grains (secondary pores) and have to be added to the present feldspar content to obtain the original detrital composition (Table 11). The original lithology of these rocks can be estimated (Fig. 16).

The abundance of rigid quartz grains, constituting the sandstone framework, probably prevented any major porosity-permeability destruction. Despite of dissolution of feldspar, the sandstone framework remained rigid and was able to withstand mechanical compaction. The feldspar content was important for the diagenesis and the petrophysical properties. The (surviving) primary porosity-permeability was enough to allow fluid circulation which led to feldspar dissolution. The decomposition of feldspars was a turning point in the diagenetic history of these sandstones and the ratio between quartz and feldspar grains is probably the crucial factor finally leading to good reservoir quality of the Bentheim sandstone. The dissolved feldspars were important in two aspects: (1) feldspar dissolution created secondary porosity and caused enlarged pore connections, thereby enhancing the permeability, and (2) it probably caused local precipitation of kaolinite. Oversized pores, resulting from complete feldspar grain and/or rock fragment dissolution, are very common and are considered to effectively enhance the porosity (Schmidt and McDonald 1979). Both the secondary pores and the authigenic kaolinite had significant effect on the porosity and permeability.

Microporosity was created by incomplete feldspar dissolution, commonly mainly affecting cleavage planes or twinning boundaries (indicated by irregular and angular grain shapes). Precipitation of authigenic kaolinite also created microporosity. Authigenic kaolinite is likely to be the result from feldspar kaolinitisation/dissolution. The development of secondary porosity and precipitation of kaolinite-dickite is probably suggesting circulation of acidic fluids generated by meteoric water and/or CO<sub>2</sub> released by underlying kerogen rich shale beds (The Posidonian Shale) as part of the kerogen maturation process (Fig. 2). The presence of the nearby Schoonebeek oil field evidences that oil generation was important in this part of the basin. In some samples quartz dissolution is unequivocal, probably due to pressure dissolution.

Table 11. Mass balance calculation for reconstructing the original feldspar content.

Sample Name	Feldspar content (%)	Secondary Porosity (%)	Original feldspar content (%) = Secondary porosity + remaining feldspar %
B	2.0	9.3	11.3
G1	0.6	13.0	13.6
G2	2.6	12.3	14.9
G4	1.0	13.3	14.3
G5	2.6	13.6	16.2
G6	2.6	18.3	20.9
G7	3.6	9.6	13.2
G8	2.0	19.3	21.3
G27	2.3	14.0	16.3
G28	2.3	17.6	19.9
G-29	2.3	21.3	23.6
G30	2.3	20.0	22.3
G31	-	-	-
G32t	2.0	8.6	10.6
G33	3.3	14.3	17.6

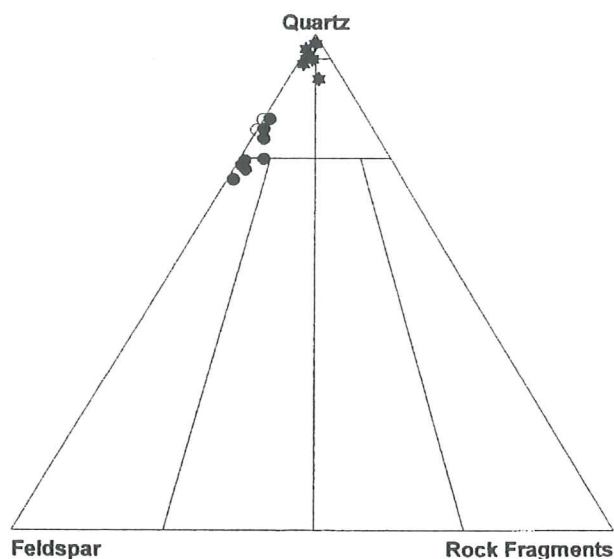


Fig.16: Plot of the present day composition (marked with an asterisk \*) and the reconstructed original detrital composition (filled + open circles) of the Bentheim sandstones (cf. Folk 1968). Although the sandstones at present are mainly quartz arenites, originally they were arkosic arenites and subarkosic arenites (according to the classification system of Folk 1968).

Detrital components control the intensity and nature of initial petrophysical modifications. This factor (compositional control) is implicitly integrated with other important factors such as diagenetic fluid circulation (chemical compaction) and basin history (time, temperature and depth, i.e., mechanical compaction). If sandstone composition is dominated by easy-compacted grains, then physical compaction will continue until almost total. As this kind of compaction is considered irreversible, there will be no chance for pore fluids to penetrate into rock fabric and cause any substantial modifications. In the case of Bentheim, sandstones, the quartz-rich sandstones could withstand the burial (effective stress) and initial porosity survived despite being reduced by quartz cementation and precipitation of authigenic kaolinite. The preserved permeability was high enough to allow fluid circulation which led subsequently to significant modifications in terms of creating new generations of porosity (secondary porosity) through dissolution of unstable feldspar and lithic rock fragments. The unstable feldspar grain decomposition probably functioned as an important internal silica and aluminium source. This provided the ions for precipitation of kaolinite and for (at least part of) the silica cement on nearby (suitable) detrital quartz grains, and thereby effectively strengthening the framework of these reservoir rocks and prevent the destruction of newly formed secondary porosity. On the other hand the partial dissolution of feldspars and some lithic grains produced microporosity which not necessarily improves the total porosity. The precipitation of kaolinite clay minerals in association with the feldspar dissolution might be an important sink for silica as well as for aluminium. The silica consumption by kaolinite authigenesis probably competed and limited the amount of quartz overgrowth development. Furthermore it can be argued that the temperature during which feldspar dissolution and kaolinite authigenesis took place played an important role in determining the reservoir quality of the Bentheim sandstone. The fact that a mixture of kaolinite and dickite has been precipitated point to moderately high temperatures, below temperatures needed for illite precipitation. The presence of dickite, which is thermodynamically more stable than kaolinite (Worden and Morad, 2000; Morad et al., 2000) would shift illitisation of kaolinite to higher temperatures, and delaying the negative effects of (fibrous) illite on permeability.

## Diagenetic processes in quartz-rich sandstones (theoretical aspects)

### Introduction

Quartz cementation and chemical compaction are the main diagenetic processes influencing reservoir quality in quartz-rich sandstones (Houseknecht 1987). Mechanical compaction through grain rearrangement is restricted to shallow burial depth in quartz-rich sandstones, whereas chemical compaction or clay induced chemical compaction may occur under intermediate and deep burial conditions. These processes and their impact on petrophysical properties are reviewed and the influence of primary detrital composition on these processes are discussed below.

### Mechanical compaction

The process of volume reduction due to the effective stress caused by the load of overlying sediments, which in turn produces a tighter grain packing, is a main cause of porosity loss of sediments. Many factors have an impact on the intensity of mechanical compaction, including fluid saturation, sorting, grain shapes, and rigidity of grains. Mature sandstones containing high amounts of rigid quartz grains lose porosity at low rates. Immature sandstones containing less rigid grains and with significant amounts of soft rock components, will consequently lose porosity at faster rates and rarely retain porosity. Porosity loss due to mechanical compaction is amongst other things a function of depositional components. Giles (1997) concluded that clay-rich sandstones lose porosity at a faster rate than quartz-rich sandstones do. Four major mechanisms contribute to porosity loss by compaction (Wilson & Stanton 1994), mechanical compaction being responsible for much porosity loss especially at shallow burial depths, viz.

1. Grain rearrangement: the rotation and slippage of grains into more stable packing positions. This is a mechanism merely independent of grain composition.
2. Plastic deformation: plastically bending or deformation of grains into sandstone pores. Evidently plastic deformation will mainly occur in the easily deformable lithic grains.
3. Brittle deformation: some types of sandstone grains might exhibit brittle fracturing at low temperatures.
4. Pressure dissolution: this process is of great importance and can be regarded as a physicochemical process, i.e., both chemical and physical processes are involved in pressure dissolution. Because this process is probably regarded as one of the main silica yielding mechanisms and can directly be attributed to the process of quartz cementation (development of quartz overgrowths) it will be dealt with later under the subject of quartz cementation itself. The onset of pressure dissolution depends on the mineralogical composition and specific solubility of the sandstone grains.

The rigidity of the framework is probably the main factor behind porosity preservation during mechanical compaction. Quartz grains are considered very rigid and the lack of natural cleavages and twinning in quartz grains will hinder grain fracturing and enable a sandstone mainly composed of quartz grains to withstand high vertical stresses due to overburden pressure. It has to be said that mechanical compaction is integrated with chemical stability of the grains. In cases of physically stable but chemically unstable grains, dissolution of grains due to interstitial fluid circulation will lead to severe weakening of the framework and promote compaction related processes. Consequently the rate of porosity loss will be substantial.

### Chemical compaction and clay induced chemical compaction

Dissolution of chemically unstable grains will result in framework weakening, thus paving the way for further grain rearrangement (and a tighter packing) by mechanical compaction. Pressure at grain contacts may play a role in increasing the solubility and enhance the effectiveness of circulating dissolving fluids. It is widely believed that clay abundance at grain contacts may promote chemical compaction, i.e., pressure dissolution (Bjørkum 1996). Although clay coatings may prevent quartz cementation simply by blocking the nucleation sites for quartz precipitation (reducing the grain surface area for precipitation) (Pittman & Larsse 1991; Ehrenberg 1993) they also tend to promote pressure dissolution, a process which probably is better called clay-induced dissolution of quartz grains. Evidently pressure dissolution is promoted only in cases when these clays are thin and discontinuous.

## Quartz cementation

Quartz cement results from heterogeneous precipitation in suitable nucleation sites such as detrital quartz grains. These overgrowths are optically continuous with the commonly detrital nucleation sites, having the same crystallographic orientation. Quartz cement is a common diagenetic phenomenon in quartz rich sandstones (important hydrocarbon reservoirs in many basins worldwide) and is believed to have harmful impact on main petrophysical properties (porosity-permeability). Thus, the issue of the diagenetic processes involved in quartz cementation is a major concern for many petroleum geologists working in the field of reservoir quality evaluation. In order to decrease the large uncertainties in reservoir quality assessments, source(s) of these silica cement, controls on the processes behind the transportation and precipitation of these cements (quartz overgrowths) must be clearly understood (Kupecz et al. 1997). The ion sources needed for precipitation of quartz cement is always an uncertainty and poses a serious problem in terms of quantity, the source (internal or external) and the processes involved. The temperature has been suggested as a main factor in controlling authigenic quartz precipitation (Walderhaug 1994), as well as in the silica releasing diagenetic processes (Worden and Morad, 2000). It has also been suggested that the intensity and the amount of quartz cements increase with temperature and thus burial depth (Bjørlykke and Egeberg 1993; Walderhaug 1994). However, in contrast to this, some workers report that quartz overgrowths are also phenomena of low-temperature environments (Primmer et al. 1997). These discrepancies (source, volume, controlling factors, processes etc.) will certainly cause a large variability if attempts are to be made to construct general trends for reservoir quality predictions.

Cementation is the process of physical connecting grains by precipitation of new, authigenic crystalline components, i.e., the process of the formation of new crystals in the sandstone pores, which physically bind sandstone grains together. The cements commonly have the same mineralogical composition as the grains but also may have a different composition. In general, many minerals can be regarded as cement materials but some minerals are more common than others. Quartz cements are certainly the most important cementing material in quartz-rich sandstones and it may cause severe damage to porosity and permeability if they are present in large quantities. Besides quartz, carbonate minerals are also main cements in quartz-rich sandstones. In petroleum exploration programs, understanding the intensity, distribution, and phenotype (overgrowth, outgrowth) of quartz cements is of crucial importance. This gives direct evidence of porosity-permeability evolution in sandstone reservoirs, thus controlling the prospect management (reserve estimations, production rates and future field developments). Many workers consider that quartz cementation is attributable to pressure dissolution (as the main contributor to silica budget and an influential process to silica transportation and precipitation (Bjørlykke and Egeberg 1993; Renard et al., 2000; Giles 1997). The effective stress imposed at grain contacts is probably the beginning (threshold) of the long and complex process of pressure dissolution. Firstly by increasing the solubility of quartz grains at grain contacts, and secondly, this stress is creating a condition of increased concentration gradient difference, which promote the diffusion procedure. It is worth noting that effective stress reduces the water film at grain contacts which is very much needed for solute transportation through the process of silica diffusion. The increasing effective stress should also be accompanied with increasing temperature, which is crucial for quartz dissolution (increasing quartz solubility).

A number of processes are to be considered to play role in quartz cementation. Among these are the cooling of hot diagenetic fluids and associated oversaturation with respect to  $\text{SiO}_2$  (the solubility of quartz decreases with decreasing T and P), the mixing of fluids with different chemical compositions which may cause supersaturation with respect to  $\text{SiO}_2$  with saline waters, and the lowering of pore pressure and evaporating of an undersaturated fluids. The silica can come from many different sources (Coleman and Eggenkamp 1994; Bjørlykke and Egeberg 1993). Giles (1997) has summarised the sources of silica which to his opinion are important:

1. Dissolution of feldspars;
2. Dissolution of heavy minerals: this can only be a minor source of silica because the low average content of heavy minerals;
3. Illitisation of smectitic detrital clays;
4. Dissolution of silt- or clay-sized quartz grains and reprecipitation as overgrowths on larger quartz grains (Oswald ripening);
5. Dissolution of unstable silica polymorphs, e.g. amorphous biogenic silica or volcanic glass;
6. Stylolites and pressure dissolution;
7. Up-dip cooling of formation waters in structurally favourable positions;
8. Possible contributions from reactions other than illitisation in interbedded shales such as pressure dissolution of silt-clay sized feldspars and quartz.

Pressure dissolution along stylolites and between quartz grains and mica/illite clay surfaces are considered internal sources of silica (Bjørkum et al. 1998) acting within the reservoir sandstone bodies. In some cases this could account for yielding enough Si for the authigenic quartz cement without any need of external transport mechanisms. Furthermore, volcanic material, radiolarian ooze and other sources could possibly contribute to the total volume of authigenic quartz encountered in reservoir rocks.

Feldspar dissolution is probably an important source of silica if they were fairly abundant in primary composition of sandstones. The proximity to nucleation sites make the transport of dissolved solutes to nucleation sites a reasonable scenario, especially in cases of substantial and extensive dissolution. Dissolution of feldspar grains are to be considered as silica-cement producer as these grains (feldspars) characterised by richness in Si and Al components, even in cases of clay mineral replacements there will be still some excess rates of these components (Al, Si) (Worden and Morad, 2000). Pressure dissolution becomes probably important at intermediate-deep burial depths of 2.5-3km (and elevated temperatures) in contrast to dissolution of amorphous silica, which is a possible Si source at shallower depths of 1.5-3.0 km (Bjørlykke and Egeberg 1993). There are reasons to expect that in each basin a particular source of silica cement could be the dominant one and be a main contributor to the silica budget. One should keep in mind that other sources still can contribute to that budget depending on the initial composition of the rocks in question, burial and diagenetic history of the basin.

The circumgranular cement forms when many nucleation substrates are available on a detrital sand grain in contrast to poikilotopic cements which forms when only few nucleation sites are available. The mineralogy and grain size of detrital grains are also playing a major role in controlling the intensity of quartz overgrowths, because different detrital minerals (different mineralogy and grain size) show different intensities of quartz cement. Heald and Renton (1966), based on laboratory experiments, concluded that monocrystalline quartz grains exhibit a increase in amount of cementation with decreasing grain size. This is probably due to the specific surface availability for precipitation of authigenic quartz cements as quartz cementation is controlled by the availability of nucleation surface per volume unit. Concerning polycrystalline quartz grains, the size of the composing crystals is an important factor controlling quartz cementation. The amount of cement declines with decreasing crystal size. As has been shown by Heald and Renton (1966), fine-crystalline quartzite grains exhibit moderate and chert grains show the slightest amount of quartz cementation. Therefore many conditions should be fulfilled before any substantial formation of cement overgrowths take place. A proper pre-existing quartz nuclei is of profound importance besides the physico-chemical conditions and a nearby source of silica which should be capable of generating adequate dissolved cement material. In many cases of evaluating quartz cementation and the silica budget, a single source of cementing material is largely insufficient. The surfaces of the quartz nuclei should not be shielded with other products such as clay mineral particles or clay coatings, microcrystalline quartz coatings, or iron oxide coatings (e.g., hematite). These coating materials will, in particular when thick and continuous, effectively hinder the precipitation of quartz overgrowths. The minerals constituting clay coatings are deposited either in the form of detrital clay minerals which got mechanically infiltrated into the quartz sand, or which are authigenically precipitated clay minerals (coatings which in fact are clay cement) or developed from allophane like precursor precipitates.

It is worth noting that micro-quartz coatings may have caused many cases of the prevention of quartz overgrowths to form, see for example the publication of Ramm et al. (1997). These microquartz crystals are favoured in cases when the supersaturation of interstitial fluids is high enough with respect to quartz for free crystallisation (homogeneous-heterogeneous nucleation). The micro-crystals occur either as polynuclear coatings on the surface of detrital quartz grains or as discrete crystals or aggregates of crystals in the pores (Worden and Morad, 2000). The abundance of unstable volcanic material, amorphous silicates, and opaline silica are largely regarded as undesirables concerning reservoir quality. In general these materials are susceptible to diagenetic alteration and poorly sorted thus efficiently contribute in depositional porosity-permeability reductions. On the other hand, the dissolution of these materials is likely to be behind the production of precipitation of microquartz crystals through rapid supersaturating of the pore fluids.

## Physico-chemical and geological controls on quartz cementation and subsequently porosity-permeability evolution in sandstone reservoirs

The main factors which can influence quartz cementation are temperature, pressure, oil emplacement, age of the host sediment, clay content, fluid composition, fabric, burial history, and reservoir composition.

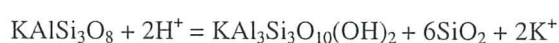
Although many factors affect quartz cementation temperature is considered significant, determining the rate and intensity of authigenic quartz precipitation. Many workers claim that in basins with high geothermal

gradients, the porosity loss of sandstones reservoirs is more rapid compared to basins with relatively lower ranges of geothermal gradients. Temperature is influencing the whole process of quartz cementation starting from the early stages of silica generation (the silica source) until the late stages of quartz nucleation on detrital host grains. Also all minor process (advection, dissolution, diffusion) in between these two main process (silica generation and silica precipitation), which directly control the outcome of quartz cementation, are strongly affected by the temperature. The most important diagenetic reactions, which are listed below, are strongly temperature dependent:

1. The formation of kaolinite ( $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ ) through dissolution of K-feldspar ( $\text{KAlSi}_3\text{O}_8$ ) :



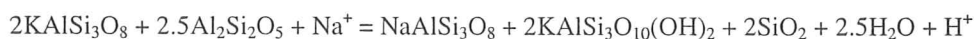
2. Illite formation by K-feldspar dissolution at the lower end of range of temperatures associated with quartz cementation (Worden and Morad 2000):



3. Illite formation by K-feldspar and diagenetic kaolinite reactions take place under elevated temperatures (~125°C):



4. Albitisation of feldspar is also a temperature dependent reaction :



As temperature increases as a result of continuous subsidence the stability fields of minerals involved in diagenetic alterations are shifted. The minerals adapt themselves to the new physicochemical conditions such as temperature increase and changes in fluid chemistry, pH, pressure etc. The transformation of one mineral or ( a particular phase) to another is extremely important in studying sandstone diagenesis and consequently they directly influence the evolution of porosity and permeability in sandstone reservoirs. These transformations can significantly modify the so called silica budget (quartz cement). In some cases they consume silica and providing silica in others. Some minerals increase the degree of crystallinity in respond to physicochemical (temperature, pressure, fluid chemistry, pH, etc.) changes. The formation of some new minerals will cause an increase in microporosity (e.g., kaolinite) but does leave the total porosity unchanged.

The pressure impact on quartz cementation is a complex factor which is not clearly understood. Many scientists claim that the process of silica production is pressure controlled. Due to the imposed pressure the solubility of quartz grains is increased at the grain contacts yielding silica for quartz overgrowth development. Two categories of pressure have to be considered in reservoir systems:

1. Fluid pressure (hydrostatic pressure)
2. Lithostatic pressure

The hydrostatic pressure is exerted by the fluid phase and the lithostatic pressure by the weight of the overlying rock column. The fluid pressure is supporting the framework of reservoir rocks in contrast to the lithostatic pressure which is consistently pressing for a tighter (closer) grain arrangement (packing). Fluid pressure is assessed taking normal hydrostatic pressure as reference. When the lithostatic pressure is greater than the hydrostatic pressure the system is normally pressured. Conversely, when the fluid pressure is greater than the reference (hydrostatic) pressure, the reservoir rocks is over-pressured (abnormally high pressured). The formation of overpressure is not well understood. The decrease of porosity due to effective stress (the difference between lithostatic and fluid pressure) imposed by the rock-column should be accompanied or preceded by expulsion of the pore fluid. The rate of fluid expulsion is probably relatively proportional with the amount of porosity reduction. In some circumstances, the pore fluid is not expelled at the rates needed for the progressive porosity reduction process. This process itself can be considered as in favour of preserving higher amounts of porosity in overpressured reservoirs than could be expected under normally pressured conditions. More interestingly, some workers claim that overpressured sandstones tend to have less quartz cement than normally pressured sandstone reservoirs as a result of insignificant pressure dissolution due to a lesser amount of effective stress and subsequently ineffective solubility increasing at



grain contacts.

For a long time, some scientists have claimed that emplacement of oil helps porosity-permeability to survive some of the destructive diagenetic processes (chemical compaction; cementation). One can speculate that oil emplacement will displace the diagenetic aqueous fluids needed for cement precipitation. In other words, the oil saturation will shut-off the fluid flow as needed for diagenetic alterations, and probably slow down diffusion as well. Although this argument seems understandable, the aspect of wettability which directly controls the total removal of diagenetic fluids at grain surfaces severely complexes the scenario. In case of oil wet systems, a number of diagenetic processes would totally halt, such as, for instance, the process of cementation. In water wet reservoir systems a thin water-film surrounds the grains, even in highly oil saturated reservoirs. One can justify the speculation of continuous diagenesis even after oil migration into such reservoir rocks, as these water-films provide sufficient means for diagenetic solute transportation by diffusion enabling precipitation of authigenic minerals. However, it is reasonable to conclude that the intensity of the diagenesis is drastically diminished because of increased pore tortuosity and complex diffusion paths. In oil-wet systems the process of oil emplacement probably halts the mechanism of diagenetic cementation completely. Although it is largely unreasonable to expect 100% oil wet systems or 100% water wet systems, one can speculate that in reservoirs with more oil wet minerals the pore system becomes more tortuous and the silica transportation pathways would be longer and quartz cement precipitation would be noticeably more time consuming. The issue becomes even more problematic when different minerals in a heterogeneous reservoir rock exhibit different habits of wettability. In order to correctly assess the impact of the oil emplacement on sandstone diagenesis, the timing of reservoir saturation with hydrocarbon must be estimated accurately and the composition of the host rock (siliclastic versus carbonates, authigenic minerals and type of clay minerals etc.) must be determined. The wettability of minerals is a complex function of fluid chemistry, pH, the mineralogy and even the texture of the solid phase (Barclay and Worden, 2000). Single kaolinite minerals and illite are often oil wet, whereas kaolinite booklets (dickite) are water wet (Barclay and Worden, 2000). Thus, theoretically, the existence of oil wet mineral grains is a preferential case and it is in favour of a lesser degree (intensity) of quartz cementation and subsequently preservation of considerable porosity. Although in the same region a number of hydrocarbon reservoirs occur in the same sandstone formation, the studied samples in this project do not show evidence for the former presence of hydrocarbons in the sampled sandstone bodies. Depending on the timing of hydrocarbon emplacement, similar or better reservoir quality could be expected for the reservoirs in the region, such as the Schoonebeek field.

The age of reservoir rocks is probably the most easy-to understand factor effecting sandstone diagenesis. In general the younger the reservoir rocks, the better reservoir quality is to be expected. It can be argued that with increasing time there is more chance of the sandstone getting into conditions suitable for cementation and compaction. On one hand because that the statistical explanation (the more time the greater probability) does make sense. On the other hand almost all diagenetic processes are largely time dependent, at least under low temperature conditions, whereas chemical processes speed up with increasing temperature. In other words, if a reservoir unit spends a long geological time in a sedimentary basin, there will be more chances for these rocks to experience different events (episodes) of modification (porosity and permeability enhancement and/or deterioration) in accordance with continuous basin evolution history. A single diagenetic process might need millions of years to reach a point where it has significant affect on reservoir properties. Therefore, geological young reservoirs have a high priority in most prospecting programmes, at least until recently (Bjørkum et al. 1998).

Clay minerals occur in almost all sandstone reservoirs having great impact on reservoir performance and quality. Clay minerals are playing a key role in oil production programmes especially during enhanced oil recovery as the injected fluids (often water) react with some clay minerals (in particular with expandable clays, such as smectite). Expansion of even small quantities of clays may cause severe damage to reservoir quality by decreasing the permeability. The type, form and distribution of clay minerals has to be studied carefully when evaluating reservoir units as each type of clay has a different impact on porosity and permeability. Many authors (Wilson and Stanton 1994) claim that fibrous illite (with large surface areas) has little effect on porosity but is severely damaging permeability as the fibres (thread-like crystals) grow radially from pore walls or occur dispersed throughout the intergranular pores, thereby creating microporosity. The illite crystals bridge the pore throats and thus block the pore connections for fluid flow. In contrast to illite, thick, blocky kaolinite booklets (with relative small surface areas with respect to volume) mainly reduces the porosity and leaves permeability within the system almost unchanged. The microscopically small clay particles have large specific surfaces and therefore they are to be considered as effective sites of many diagenetic reactions and they certainly have profound influence on the process of quartz cementation. Again the phenotype of clay minerals is to be considered while assessing the role clays might have in quartz cementation processes. Thin, discontinuous clay grain coatings might catalyse the process of pressure dissolution (this process would be better called clay-induced pressure dissolution) which subsequently provide silica needed for quartz overgrowth development. In contrast to this speculation, thick and continuous clay coatings, which shield the entire grain, can indeed impede pressure dissolution and subsequently halt quartz

cementation (as overgrowths). Most likely, coatings composed of clay cements usually with the platy or fibrous crystal axes perpendicular to the grain surface (thus a radial fabric) retard pressure solution (or clay-induced dissolution at grain contacts) because of minimum grain surface at contact sites. They also prevent quartz cementation when being continuous because they also shield the detrital quartz grains, which are the nucleation sites for quartz cement precipitation. Clay coatings with a tangential fabric (that includes all mechanically infiltrated clay coatings (clay cutans) will prevent quartz cementation in the same way (Molenaar 1986). It seems from former observations that when clay cutans are thick, they prevent or at least do not promote pressure dissolution, but when thin they indeed catalyse pressure dissolution.

Fluid chemistry has a major impact on porosity and permeability evolution. In attempting to explain why chlorite is more efficient in inhibiting quartz cementation (overgrowths) than illite clays (which is largely engulfed by quartz overgrowths), Morad et al. (2000) suggested that this could be due to chemistry of the fluids that are in equilibrium with chlorite and not the effect of the mineralogy itself. Mineral solubility is a direct function of geochemical conditions within reservoir systems for instance quartz solubility increases with increasing pH (during circulation of alkaline fluids), in contrast to carbonate minerals which generally exhibit increased solubility with decreased pH (under circulation of acidic fluids). Again it has to be stressed that a single factor can't reliably account for complex diagenetic events. In order to accurately assess a diagenetic phase many factors have to be combined and integrated together, fluid composition should always combined with temperature, pressure, time, wettability etc.

Fabric is a generalised concept which includes texture (grain to grain relationship, i.e., the spatial orientation of the grains and the crystals which form reservoir rocks etc.), structure, grain shape, grain size, packing etc. all of these parameters strongly associated with provinces, sedimentary processes, depositional environments and burial history (depth and time effect). These parameters largely determine porosity and permeability of reservoir rocks and subsequently play an important role in later modifications caused by diagenetic alterations. The relationship between each of these parameters with porosity and permeability is not always significant and would be a difficult task to construct a generalised model, which can be applied to all basins. One simple explanation for this is the extensive dissolution of the framework and substantial precipitation of diagenetic cement mineral within interstitial pores would vandalise the imprint of these parameters (reservoir fabric). The most important parameters involved are:

1. Grain shape. Porosity and permeability are largely reduced by decreasing sphericity and roundness. Reservoir rocks rich in elongated or platy grains of feldspar are more susceptible to mechanical compaction and thus faster and more porosity loss can be expected than reservoirs with fewer of these grain types (Bloch 1994a, b).
2. Grain size. Empirically, porosity is not depending on grain size in contrast to permeability which increases with increasing grain size (and diameter of pore connections). The fact that some empirical models suggest a proportional correlation between porosity and permeability could be justified by an explanation that large grain sizes will lead to diminished cementation due to smaller specific surface areas (for cement nucleation), which in many cases is a direct control on diagenetic modification of both porosity and permeability. Small grain sizes may acquire greater amounts of cement. Therefore, greater quantities of quartz cement (overgrowths) are to be expected in fine-grained sandstones. This should be a parameter to be included in constructing an analytical model for porosity and permeability predictions.
3. Packing is another important factor which effect reservoir quality (porosity and permeability). Generally, a tight (close) packing has a negative effect on porosity and permeability in reservoir rocks. Packing is a complex function of detrital framework rigidity, grain orientation, grain angularity, sorting and burial history (depth, time, temperature etc.). As most reservoirs suffered compressive stresses caused by overlying loads, tighter packing through mechanical compaction is an unequivocal process but can be arrested by cementation. Even small quantities of (early) cement can strengthen the framework and assist the grains to withstand compaction.

It is obvious that permeability and porosity evolution are greatly influenced by burial history (Salem et al., 2000). Reservoirs with dissimilar paths of burial history seem to have significantly different outcomes of diagenetic alteration and subsequently distinct reservoir properties (porosity, permeability). different Burial history in sedimentary basins and the different impacts on reservoir quality is one of the reasons why it is appropriate to claim that reservoir quality modelling is largely a basin-specific issue and attempting to construct models which can be applicable to all basins will lead to biased and unreliable results. Therefore a reliable modelling should always take burial history of the basin in question into account (for instance Exemplar principles for sandstone diagenesis modelling) (Lander and Walderhaug 1999). A burial history diagram should be able to demonstrate the residence time for each time step, possible overpressure effects within reservoir systems, uplifting evident (exposure) which

can be suggestive to potential meteoric water circulation and the profound consequences regarding dissolution (secondary porosity) and/or precipitation of cement materials (quartz cementation as active circulation might function as transportation means) which is believed to be in many cases attributed to uplifts and unconformities.

## Conclusions

- The (limited) degree of cementation by quartz was probably sufficient for strengthening and stabilising the sandstone framework to withstand the imposed effective stress and accordingly largely limit the porosity-permeability destruction by mechanical compaction. The great amounts of rigid, chemically stable quartz detrital grains associated with limited amounts of unstable (diagenetically susceptible) grains which potentially could provide material for cementation is of crucial importance. The stable grains supported the framework and consequently the oversized secondary pores by feldspar dissolution were preserved and did not cause framework collapse by mechanical compaction. The chemical stability of most grains prevented significant cementation. Thus, the high porosity and permeability of the Bentheim sandstones are partly due to the preservation of primary porosity, by limited quartz overgrowth and by the forming secondary mouldic porosity through dissolution of feldspars.
- The original detrital composition of the Bentheim sandstones is inferred to have been much more feldspar rich than the present day composition. A large part of the detrital feldspar grains (plagioclase feldspar and K-feldspar) has been dissolved during burial diagenesis. The detrital feldspar content has a profound effect on modifying the primary petrophysical properties (porosity-permeability). The oversized (secondary) pores were formed due to dissolution of detrital feldspar grains at shallow burial depth. Open or semi-open chemical conditions which may have forced the solutes of dissolved material out of the reservoir system are to be considered a very important source of porosity enhancement.
- Dissolution of detrital feldspar could have produced silica and aluminium for precipitation of authigenic kaolinite and for the development of quartz overgrowths. Authigenic kaolinite is a sink for both Si and Al and therefore possibly is competing with quartz cementation. The conflict is thus between quartz precipitation in overgrowths and kaolinite precipitation. Authigenesis of kaolinite is thus taking place at the expense of quartz cementation. Therefore, limited amounts of authigenic kaolinite development are not so much harmful for the reservoir quality since this process might create a condition of silica deficiency (insufficient silica budget) and thus thereby prevent substantial quartz cementation (as overgrowths). The presence of authigenic kaolinite and dickite, in the form of blocky, well-crystalline booklets, suggests relative high temperatures, but not high enough for illite precipitation although potassium must have been available through K-feldspar dissolution. However kaolinite affected permeability significantly. The potassium (from K-feldspar dissolution), and possibly also Ca and Na (from plagioclase feldspar dissolution) evidently have been transported out of the sandstone system, evidencing that the diagenetic system was at least partly open.
- The optical point counting technique is subjected to large error and uncertainty especially in cases of quartz overgrowth cement quantification. It is recommended that conventional point counting is used with great caution and if possible always to be integrated with images and image analysis on images obtained by other techniques such as CL and SEM-BE. Thus point counted data from polarised-light images should be calibrated by more accurate methods in order to get more reliable results.

## Acknowledgments

This work would never have being possible without the generous help from my supervisors Dr. Niek Molenaar at the Technical University of Denmark (DTU) and Dr. Anders Ahlberg at Lund University (LU). I am very much indebted to their support, kindness and thoughtful reviews. I furthermore would like to extent my thanks to Sinh Nguyen, who helped me with laboratory analyses, to Hektor Diaz, which prepared my thin sections and core plugs, and to my friend Jarl Kobbarnagel for his support during the course of this project. Prof. Kent Larsson and secretary Margaretha Kihlblom at LU are thanked for support of my study. Geologica is acknowledged for giving me the chance to test the *Exemplar* software package.

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