Because turbidites are deposited further away from land, they are less exposed to flushing by meteoric water. Turbidites normally contain less evidence of feldspar dissolution and authigenic kaolinite precipitation than shallow marine and fluvial sandstones. In proximal turbiditic facies, however, the sandstones may have good contact with the meteoric water lens. In the North Sea, Tertiary turbidites generally have a relatively low content of authigenic kaolinite, but it may be higher in proximal Cretaceous turbidities which formed around islands produced by local uplift.

The total flow of meteoric water through sandstones is a function of meteoric water flux and the sedimentation rate. At low sedimentation rates a given volume of sand spends more time in the shallow zone of meteoric water flushing.

Cretaceous and Tertiary turbidite sandstones are often very tight due to pervasive carbonate cement. This may be due to pelagic carbonate organisms being mixed in with the turbidite sand and recrystallising into carbonate cement. This makes many Tertiary sandstones hard and indurated even if they have not been buried very deeply.

Many of the planktonic carbonate organisms developed during the Jurassic, so before then the sources of carbonate cement in deep sea sandstones were more restricted.

4.16 Practical Predictions of Reservoir Quality and Porosity Depth Curves

The oil industry has a practical need to be able to predict the properties of reservoir rocks ahead of drilling. When planning petroleum production the rock properties between the wells must also be estimated. Particularly in the deeper reservoirs, porosity is the most important factor determining the economic viability of a prospect. The main diagenetic processes with quartz cementation are summarised in Fig. 4.15.

In a relatively mature basin the porosity/depth functions of the different reservoir rocks can be treated statistically so that the uncertainty of the estimates can be expressed. The estimates based on the statistical averages can also be adjusted up or down as a function of temperature, stress etc., depending on what the interpreter considers most significant. The Middle Jurassic Brent sandstone in the North Sea has been intensively studied and a relatively linear trend found between burial depth and porosity (Giles et al. 1992, Bjørlykke et al. 1992, Ramm et al. 1992, Wilson 1994). Porosity predictions will depend on the primary sediment composition and the subsequent compaction processes.

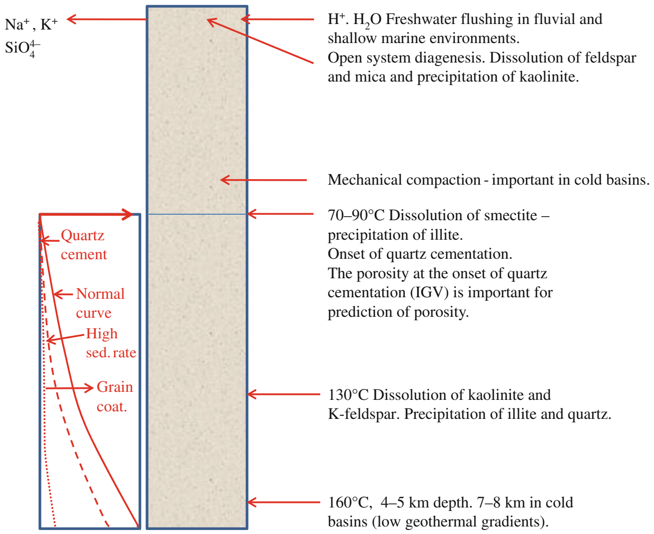

Fig. 4.15 Summary of the most important processes in clastic diagenesis. Dissolution of feldspar and mica requires a through flow of meteoric water removing K^+ (Na^+) and silica before kaolinite can be precipitated. This process is most dominant in fluvial and shallow marine sediments at shallow burial. At greater depth diagenetic reactions are nearly isochemical at a scale of 1–10 m distance. The composition of the dissolved material is equal to what is precipitated. Carbonate cements are usually derived from biogenic carbonate or clastic carbonate grains. Quartz cementation is controlled by temperature (geothermal gradients), subsidence rates and the presence of grain coatings

Above we have discussed some of the processes that cause reductions in porosity and permeability. All these processes are driven towards denser packing of grains and thermodynamically more stable mineral assemblages as the stress and temperature increases during burial. The kinetics of mineral reactions determines the rate of thermodynamic equilibration, which increases as an exponential function of temperature.

The rate of compaction as a function of stress can be measured experimentally using rock mechanics testing procedures. However, the reactions involved in chemical compaction are so slow, particularly in silicate rocks, that it is difficult to reproduce them in the laboratory although in some cases this is now becoming possible.

In the field of clastic diagenesis, petrographic observations about mineralogy and textural relationships are used to interpret the sequence of dissolution and mineral precipitation and its relationship to changes in porosity and permeability. It is however important to consider the geochemical constraints on diagenetic reactions. During burial the reaction must add up so the dissolution is balanced by precipitation because there are strong limitations with respect to supply and removal of solids dissolved in the porewater.

Changes in mineralogy or porosity with depth may provide useful depth trends within an area, but in a sedimentary basin the initial mineral compositions may vary laterally. This is also the case for early diagenetic processes like meteoric water flushing and marine cementation. The observed changes with depth may therefore also reflect some of these factors and not only the burial depth.

Based on the theory that the rate of quartz cementation is controlled only by temperature, time and the grain surface available for quartz precipitation, the amount of quartz cement and consequently the porosity can be modelled (Walderhaug 1996). The presence or absence of clay or other coatings is the most critical input for this modelling because it determines the area available for quartz cementation. Prediction of reservoir properties must start from sedimentological facies models. The depositional environment and the provenance of the clastic sediments determine the starting composition for the diagenetic processes.

Early diagenetic processes like marine carbonate cementation and meteoric water flushing are also linked to facies and they strongly influence the burial diagenesis and the porosity reduction at depth. The precursor minerals controlling the growth of chlorite coating are also probably to a large extent controlled by facies. The distribution of silica organisms (like *Rhaxella*) which can produce micro-quartz coatings is linked to the environment and ecology.

A broad geological background is therefore required to synthesise all the factors that have to be considered before modelling or making semi-quantitative predictions of reservoir quality. The capacity of porewater to keep solids in solution is always rather limited and mineral dissolution and precipitation must therefore balance.

At greater burial depth (3–4 km) the solubility of silicate minerals increases but the volume of porewater is low and the potential for supersaturation and undersaturation strongly reduced. Precipitation of new mineral phases must therefore be linked to the dissolution of other minerals or of the same mineral.

Assuming that the burial diagenetic processes are relatively isochemical, the reservoir properties can be predicted from depositional facies and provenance studies which define the starting composition for burial diagenesis. Both observations and theoretical arguments suggest that advective transport can not significantly change the rock compostion below the reach of meteoric water flow. Short distance transport by diffusion may nevertheless be important.

Quartz cementation was often interpreted to occur as events of relatively short duration (approximately <10 million years) that could start and stop late in a sandstone's burial history (Robinson and Gluyas 1992). This would imply that the quartz cementation was controlled by advective transport of silica in solution and the source of silica from other reactions. Fluid inclusion data, however, shows that quartz cementation occurs throughout the temperature range corresponding to the burial history.

Modelling of quartz precipitation (Walderhaug 1996, Olkers et al. 2000, Walderhaug et al. 2000) is based on the assumption that this is a continuous process controlled by the kinetics and therefore by temperature. This is the basis for the practical models widely adopted by the petroleum industry (e.g. Exemplar and Touchstone).

The assumption that the quartz precipitation is the rate limiting factor may not always be strictly true in clean quartz arenites where silica sources (stylolites) are widely spaced, resulting in decreasing quartz cementation away from the stylolites (Walderhaug 2003). The modelling does, however, require that the burial curve and the temperature as a function of geological time are known. It is also very sensitive to changes in the primary sediment composition, which strongly influence both the mechanical compaction and the chemical reactions. The porosity loss and increased sediment density resulting from chemical compaction as a function of temperature cause basin subsidence (Bjørkum et al. 1998, 2001; Bjørkum and Nadeau 1998). Temperature-driven chemical compaction results in a volume reduction (shrinkage) and the strain is then independent of effective stress. As a result, differential stresses in siliceous rock will be relaxed by the compaction processes during basin subsidence as long at the temperature exceeds about 80°C (Bjørlykke 2006).

4.17 Porosity/Depth Trends in Sedimentary Basins

Data from wells in sedimentary basins which have undergone almost continuous subsidence can be regarded as records of a natural compaction experiment. We can use the log porosity and in the cored intervals we have data from core plugs.

At depths shallower than about 2 km (80–100°C) we can compare the log porosities with experimental compaction of similar sands in the laboratory. There will then be a marked effect of overpressure reducing the effective stress. Poorly sorted sands will lose most of their porosity at relatively shallow depth but well sorted sand may have 30–35% porosity at 2–3 km depth, which corresponds to experimental compaction at about 20–30 MPa effective stress. This suggests that there is little creep over long geologic time.

Data from deep wells will always show a trend towards lower porosities with depth but there may also be intervals where this trend is reversed. This does not mean that net porosity has been created by diagenetic processes. Because of the very low solubility of silica and even more so of aluminium in porewater it is very difficult to explain how minerals in several metre thick sandstones can be dissolved without precipitation of other minerals in the same sandstones. Each lithology will have a characteristic porosity depth trend (Fig. 4.16) and increases in porosity reflect variations in the primary composition.

As discussed above the rate of quartz cementation can be modelled if the surface area available for quartz cementation and the time-temperature history during burial are known.

At about 4.0 km burial depth (120–140°C) the amount of quartz cement may be 10–15% so the remaining porosity may be only 10–15%. We do however find good reservoir quality (>20% porosity) at greater depths and higher temperatures but this is due to grain coatings. Prediction of porosity at great depth therefore requires that the occurrence of coating of chlorite, illite, haematite or micro-quartz can be predicted. Such prediction of the primary sediment composition must again be linked to facies and provenance.

Prospects at great depth called HTHP (High Temperature, High Pressure) are expensive to drill and involve high risks, but in many mature basins nearly all the shallower prospects have been drilled already.

An extensive study of reservoir sandstones in the Gulf of Mexico showed that temperature and time are the main factors controlling reservoir quality (Nadeau et al. 2008).

4.18 Practical Prediction of Reservoir Quality

The most important factor controlling reservoir quality at depth is the primary composition of the sandstones. Sedimentological and sequence stratigraphic analyses are normally used primarily to predict reservoir geometry, but for diagenetic processes grain size, sorting and mineralogical composition are more critical. It is imperative to establish changes in provenance since the primary mineralogy places important constraints on diagenetic reactions at depth.

Reconstructions of facies and climate will provide a basis for predicting the degree of feldspar dissolution and precipitation of pore-filling kaolinite. Biogenic components like calcareous and siliceous organisms will control the distribution of carbonate cements and opal A, which will be altered to opal CT and quartz. Primary aragonite may cause extensive calcite cementation that occludes much of the primary porosity. Organic silica, e.g. from siliceous sponges, may serve as a precursor to grain-coating micro-quartz preserving porosity at depth.

Porosity loss due to mechanical compaction can vary greatly as a function of textural and mineralogical composition. Experimental compaction of loose sands

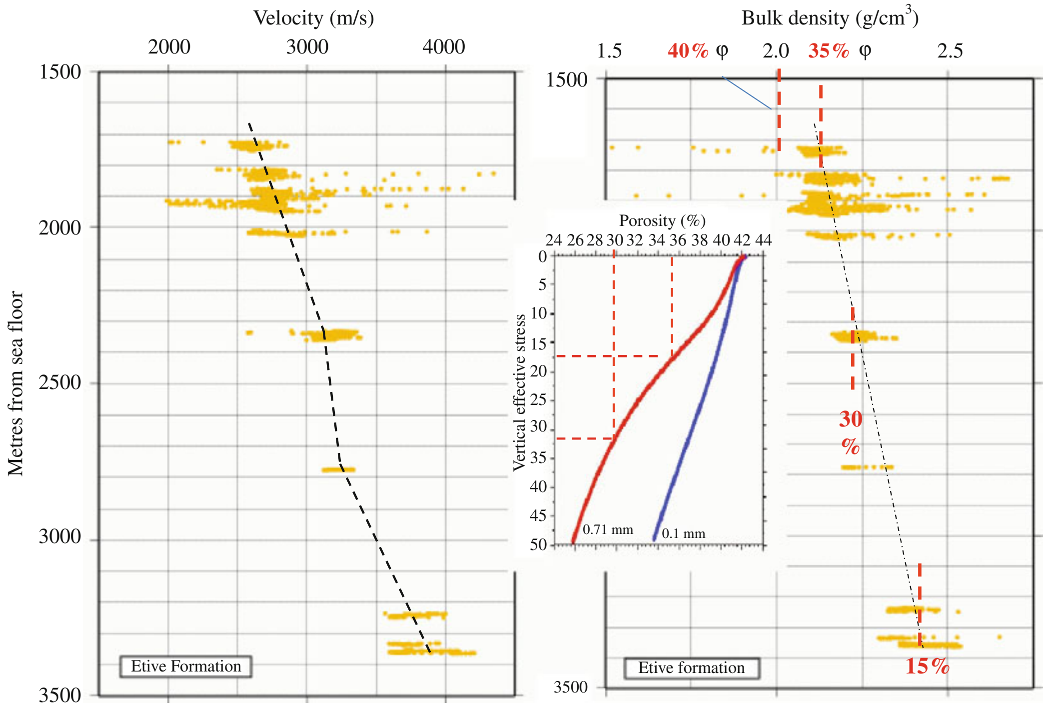

Fig. 4.16 Density/depth and velocity/depth trends for the Etive Fm (Brent Group) showing that a single lithology has a nearly linear trend with depth, based on Marcussen et al. (2009). The calculated porosities show that the compaction down to about 2 km depth are mechanical and similar to experimental data inserted from Chuhan et al. (2002). At greater depth, compaction is mostly chemical and higher compared with mechanical compaction

with different grain size and sorting provides a good basis for prediction of porosity and inter-granular volume before quartz cementation. In cold sedimentary basins (low geothermal gradient) sand may be buried to 4–5 km before there is significant quartz cementation and in the absence of overpressure it can be subjected to 40–50 MPa effective stress.

Well log data from distinct lithologies buried to different depths may also provide a useful database for predicting the porosity loss due to mechanical compaction.

4.19 Summary

Porosity loss due to quartz cementation can be modelled as a function of temperature, time and surface area available for quartz cementation. This is sensitive to grain size and grain coatings, which must be predicted from primary facies evaluation. The presence of pore-filling illite depends on precursors which may be smectite or kaolinite. Dissolution of kaolinite and precipitation of illite requires temperatures above 130°C and the local presence of K-feldspar. Sandstone containing mostly plagioclase does not develop pore-filling illite as there is insufficient supply of potassium. Prediction of reservoir quality can thus be based on provenance.

The examples of reservoir quality predictions listed above are based on the assumption that burial diagenetic reactions are essentially isochemical. Open system diagenesis allowing large scale import and export of solids in solution violates constraints from mineral solubilities and fluid flow rates and therefore provides a poor basis for prediction.

4.20 How Much Oil Can Be Produced from Sandstone Reservoirs?

Petroleum exploration requires predictions about the reservoir properties ahead of drilling to justify the investment that a well represents. The reservoir properties determine the percentage of recoverable