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Invited review

Relationships between depositional environments, burial history and rock properties. Some principal aspects of diagenetic process in sedimentary basins

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ABSTRACT

Sedimentology, sequence stratigraphy and facies analysis have for many years been disciplines rather separate from diagenesis which is concerned with processes occurring after deposition. Prediction of rock properties as a function of burial depth in sedimentary basins requires that these disciplines become more integrated. Compaction of sedimentary rocks is driven towards increased density (lower porosity) and higher rock velocity as functions of burial depth (effective stress) and temperature. Both the mechanical and chemical compaction of sedimentary rocks are functions of the primary textural and mineralogical composition of the sediments at the time of deposition and after shallow burial diagenesis. This is controlled by the provenance, transport and depositional environment. Many published sedimentological studies, however, contain little information about the mineralogical and textural composition of the sedimentary sequences.

Near the surface, sediments are in an open geochemical system due to groundwater flow, diffusion and evaporation. Here their composition may be changed by mineral dissolution and transport of the dissolved components. At greater depth, below the reach of significant meteoric water flow, the porewater has an exceedingly low mobility and capacity to transport solids in solution. The porewater will gradually approach equilibrium with the minerals present, reducing the concentration gradients in the porewater and the potential for both advective and diffusive transport of solids in solution. Significant increased porosity (secondary porosity) is dependent on the dissolution and removal of solids in solution which may occur during freshwater flushing at shallow depth dissolving feldspar and precipitating kaolinite. Below the reach of freshwater the porewater flow is limited and represents a geochemically nearly closed system. The porewater will in most marine sediments be in equilibrium with calcite, even if it occurs in small amounts. Prediction of rock properties such as porosity and seismic velocity at a certain depth in a sedimentary basin must be based on the burial history (effective stress and temperature), but the primary mineralogical and textural composition of the sediments is equally important. Studies of depositional environments and provenance should therefore be integrated with diagenesis and be a part of basin analysis which is used for basin modelling.

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1. Introduction and historical background

Sedimentology as a geological discipline developed from sedimentary petrology and the emphasis was initially the mineralogical and textural composition of sedimentary rocks as documented in textbooks like Pettijohn (1956). Optical microscopy, identifying the mineral phases present and their composition and textures was included as standard in descriptions of sedimentary rocks, both in sandstones (Blatt et al., 1972) and limestones (Bathurst, 1976), and analyses by SEM (Scanning Electron Microscope) and XRD (X-ray diffraction) became common. Grain-size analysis was commonly carried out as part of sedimentological studies (Visher, 1969). As a starting point for predicting burial diagenesis, the grain-size distribution is very important.

Modern sedimentology established models for different types of sedimentary environments, based on studies of sedimentary structures from well-exposed outcrops or cores, but textural and mineralogical studies became less common. As marine seismic data became increasingly available in the 1970s, sequence stratigraphy developed as a successful discipline that is useful in the prediction of the distribution and shape of reservoir sandstones in sedimentary basins (Vail et al., 1977). Interpretations of what was below seismic resolution were in most cases based on detailed fieldwork on well-exposed outcrops which served as analogues for subsurface reservoirs. It is, however, critical that the sedimentary sequences in the onshore analogues represented depositional environments and sediment composition that were relatively similar to those in the subsurface, particularly with respect to primary mineral composition.

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Tectonics, sea level changes and climate have been the important factors of sediment variability discussed in most sedimentological publications. Textbooks on sedimentary environments (e.g. Reading, 1986) provided many examples from different sedimentary basins. However most sedimentological textbooks contained little information about the mineralogical and chemical composition of the sediments. In the last 30–40 years a majority of publications in the field of sedimentology have been related to descriptions of sedimentary sequences from outcrops or from seismic records and interpretations of sedimentary environments. Descriptions of cores may include detailed information about sedimentary structures, but commonly little or no information about the mineralogy, both of sandstones and even more so with regard to mudstones and shales. Textbooks on sequence stratigraphy and basin analysis likewise contain little information about the mineral composition of the sediments described therein (Catuneanu, 2006; Miall, 1985). The focus of sedimentological models has been the prediction of the shape and distribution of sand bodies. Their internal properties resulting from the processes occurring after deposition – diagenesis – have often been considered to be a separate subject for specialists in this field. Many sedimentologists have not received advanced training in mineralogy and geochemistry. This is unfortunate because diagenesis should be well integrated with facies analysis in order to predict rock properties at a certain burial depth and temperature. The physical properties of sedimentary rocks are thus very much a function of the mineralogical composition which also determines the response on well logs and seismic data.

Clay mineralogy was already well established as a field in the 1950s and 1960s, though mostly as a highly specialised field which became very important for engineering geology. It was to a much lesser extent included in sedimentology, except in some more specialised books on claystones and mudstones (Chamley, 1989; Weaver, 1989; Velde and Meunier, 2008). Clay particles vary greatly with respect to grain size and also their surface properties (charge) are very different. Both smectite and illite are extremely small particles (10^{-4} to 10^{-5} mm) with negative surface charge. Kaolinite, with a grain size exceeding 0.01 mm, has lower surface charge and higher settling velocities during transport and deposition.

Mudstones are often described with respect to their appearance in outcrop and their content of organic matter (Potter et al., 2005) but it is their clay mineralogy that is the key to understanding their transport, deposition and compaction. Experimental data on the behaviour of different types of clays was widely used for predicting the compaction of mudstones and clays for engineering purposes, but was to a far lesser extent included in sedimentological models (James and Dalrymple, 2010).

In the case of carbonate sediments, the importance of the textural and mineralogical composition for burial diagenetic reactions was realised at an early stage (Folk, 1959; Bathurst, 1976; Moore, 1989). This may be because considerable carbonate diagenesis can take place at shallow burial depths which are readily accessible for observation. The primary mineral composition of carbonate rock reflects both the sedimentary environment and the evolution and ecology of calcareous organisms.

Research on the physical properties of sedimentary rocks is divided into many relatively separate disciplines which publish in different journals and have limited communication (Fig. 1). Research and education in engineering disciplines are often separate from the geological. This is unfortunate because the physical properties of sedimentary rocks are a function of provenance, weathering, transport and depositional environment, and there should be a strong link between clastic sedimentology, diagenesis and geophysics. The purpose of the present paper is to demonstrate the relationships between sedimentary environments, sediment composition (mineralogy, texture) and rock properties as a function of burial history in sedimentary basins.

The distribution and shape of different lithological units in a sedimentary basin can to a certain extent be mapped out based on seismic and other subsurface data so that the distribution of facies can be reconstructed (Fig. 2). The internal properties of the sediments such as porosity, permeability and density are more difficult to determine as they change both during burial and uplift due to mechanical and chemical compaction (Bjørlykke, 1999a, 1999b). Burial diagenesis influences not only reservoir rocks but also the lithologies in entire sedimentary sequences that make up the basin fill. Compaction processes determine the sediment's seismic response and other geophysical properties critical for fluid flow, basin analyses and for modelling, such as basin subsidence and accommodation space.

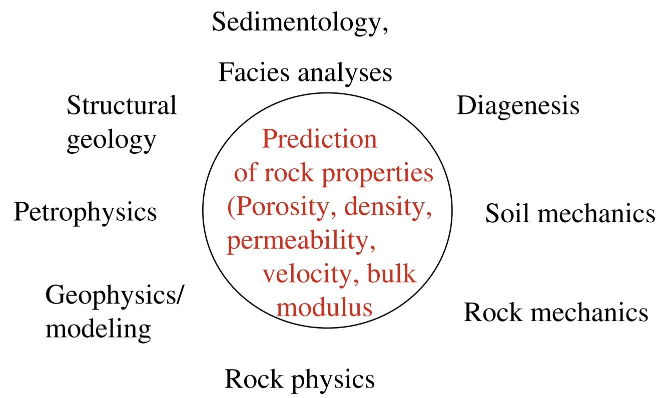

Fig. 1. Research on rock properties is unfortunately separated into many different disciplines which publish in different journals and attend different meetings. This limits the potential for more communication, integration and cross-fertilization of the research effort.

Prediction of rock properties before drilling in a sedimentary basin must be based on certain assumptions and constraints with respect to the processes involved during compaction. The most important constraint is that the bulk chemical composition of sedimentary rock remains nearly constant during burial in sedimentary basins below the reach of high fluxes of meteoric water at shallow depth. This assumption is based on calculations of fluid flow in sedimentary basins and the potential for transport of solids in solution by advection and diffusion (Bjørlykke, 2011; Bjørlykke and Jahren, 2010, 2012). Stratification in the porewater with respect to salinity is a further argument against large-scale vertical flow (Gran et al., 1992; Bjørlykke, 1993; Bjørlykke and Gran, 1994). We may say that the sediments are sinking through a column of porewater and there is normally no source of porewater in the basement. This limits the vertical compaction-driven flow.

The primary textural and mineralogical composition, related to facies and provenance, is then the key for predicting the compaction processes during increased burial. Diagenetic processes are generally not basin-wide as argued by some authors (e.g. Montanez, 1997) but more local, reflecting the sediment composition, temperature history and effective stress.

If a basin had an open geochemical system, which would allow very significant changes in the rock composition during burial as suggested by Day-Stirrat et al. (2010) and several other authors (Gluyas and Coleman, 1992; Land, 1997; Land and Milliken, 2000), dissolution and formation of secondary porosity and precipitation of cement would not be constrained by the bulk chemical composition of each sedimentary layer. If the bulk rock composition had changed significantly during burial diagenesis this would imply that the link between the sedimentological processes controlling the primary sediment composition at the time of deposition and burial diagenesis would have been much weaker.

Formation of secondary porosity and cementation without corresponding precipitation and dissolution in the adjacent beds requires large-scale mass transfer of solids in the subsurface. An open system characterised by large-scale import and export of solids in solution is thus implicit in a very large part of the literature on clastic diagenesis during the last 30–40 years (Schmidt and McDonald, 1979). Quantitative models explaining how an open geochemical system is possible

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