

A closed-system four component model for computing the porosity and permeability of sedimentary basin sandstones

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Owing to their importance in estimating the quantity and recoverability of petroleum, numerous algorithms have been developed to predict sandstone porosity and permeability in sedimentary basins. Among these, geochemical based diagenesis models are commonly limited by an inadequate understanding of the thermodynamic and kinetic properties required in the model. To overcome this limitation, a geochemical based sandstone diagenesis model is developed and used together with available experimentally measured thermodynamic and kinetic parameters to acquire field based interfacial surface areas, quartz precipitation rate constants, and illite stability constants. The resulting parameters permit accurate porosity and permeability predictions.

Description of diagenetic model

The modeled sandstone is described in the chemical system $K_2O-Al_2O_3-SiO_2-H_2O$ and has water saturated pores. It consists originally of quartz, K-feldspar, kaolinite, and muscovite. Muscovite is contained in parallel stylolites; the other three minerals are in the interstylolite region. The system is closed except for the expulsion of water during compaction. Chemical mass transfer of K, Al, and Si into or out of the system by advection is considered to be negligible. Calculation of the temporal evolution of porosity and permeability along a specified time/temperature/burial rate trajectory is performed by simultaneously considering the effects of mechanical and chemical contributions to compaction and diagenesis. The three main diagenetic processes considered are: 1) mechanical compaction, 2) quartz redistribution via the Illite-Mica Induced Dissolution (I-MID) mechanism, and 3) illite precipitation provoked via kaolinite and K-feldspar

dissolution. These three contributions are described below.

Mechanical compaction is computed using the exponential equation of Robinson and Gluyas (1992). It is assumed to proceed until 0.5 volume percent of quartz cement has precipitated. This cementation limit is typically reached when the temperature of the sandstone has reached 90°C.

Quartz cementation due to silica redistribution proceeds via the I-MID mechanism (Oelkers *et al.*, 1996, Bjørkum *et al.*, 1998). Quartz dissolves at quartz-mica and quartz-clay interfaces adjoining stylolites within the sandstone. Aqueous silica formed at this interface is simultaneously transported by diffusion into the interstylolite region and precipitated as cement on other quartz grains. Taking account of petrographic observations (Aase *et al.*, 1996), a temperature independent excess molar energy of 4.8 cal/mol was calculated to drive quartz dissolution at mica or clay interfaces. Although the energy driving this process is likely supplied by compaction, petrographic evidence indicates that differential pressure of dissolving grains is insignificant and the effect of pressure is negligible (Bjørkum, 1996).

The third process involves the dissolution and precipitation of aluminosilicate phases. In accord with petrographic observations, muscovite contained within the stylolites is inert. The main reaction among aluminosilicate phases, and the only reaction considered is K-feldspar and kaolinite dissolution provoking illite and quartz precipitation. This reaction is typically observed at temperatures of approximately 100 to 140°C. Although this reaction has only a small effect on the overall porosity of reservoir rocks, illite formation exerts a strong influence on permeability; a small quantity of pore

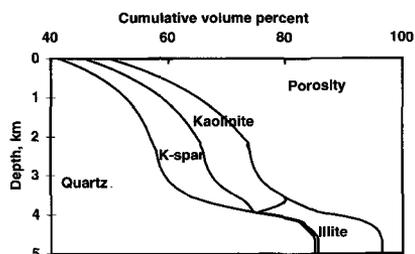


FIG. 1. Computed mineral abundances with depth (see text).

filling illite greatly reduces permeability. Regression of petrographic data from the Garn Formation (Mid Norwegian continental shelf) was used to generate quartz precipitation rates and illite stability constants for model calculations.

Computed mineralogical abundances are related to permeability (k) through the semi-empirical Konezy-Carman equation given by

$$k = \frac{\phi^3 / (1 - \phi)^2}{5\bar{s}_0^2} \quad (1)$$

where ϕ refers to the porosity and \bar{s}_0 denotes the normalized solid/pore interfacial surface area. To account for the high surface area of precipitated illite, \bar{s}_0 is taken to be the sum of contributions from each mineral present such that

$$\bar{s}_0 = \sum_{N_M} \bar{s}_{0,M} V_M \quad (2)$$

where $\bar{s}_{0,M}$ refers to the effective normalized solid/pore interfacial surface area of the M th mineral, V_M designates its volume fraction, and N_M stands for the number of minerals present in the system. Values of $\bar{s}_{0,M}$ are obtained from the regression of field data.

Computational results and discussion

The computed mineralogical evolution with depth of a sandstone initially consisting of 40 volume percent quartz, 5 volume percent kaolinite, 5 volume percent K-feldspar and 50 percent porosity, bounded by parallel muscovite stylolites with a stylolite density of 10/m is illustrated in Fig. 1. Taking conditions consistent with the Mid Norwegian continental shelf, this sandstone is 160 million years old, buried at a constant rate, and in a basin having a 35°C/km temperature gradient. Diagenesis is dominated by mechanical compaction to a depth of 2.5 km which

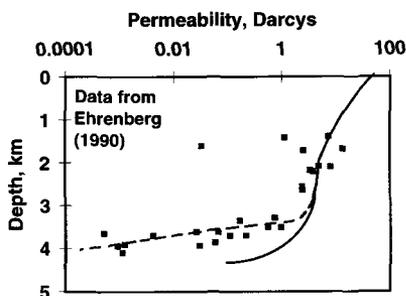


FIG. 2. Comparison between computed and measured sandstone permeabilities with depth (see text).

increases the volume fraction of the minerals present, but not the amount of one mineral relative to the others. Quartz cementation arrests mechanical compaction, and diagenesis is dominated by quartz redistribution via the I-MID mechanism at depths from 2.5 to 3.5 km. Little change in K-feldspar and kaolinite abundances occurs over these depths. At a depth of 3.5 km, kaolinite and K-feldspar dissolve provoking illite precipitation and increasing the quartz cementation rate. All the K-feldspar, and all but 0.7 volume percent of kaolinite are consumed by the illite forming reaction, which goes to completion at a depth of ~4.1 km. Following the complete consumption of K-feldspar, diagenesis is again dominated by quartz redistribution via the I-MID mechanism until a depth of 4.7 km, when the porosity reaches ~3.6 percent. At this porosity limit pore throats are closed and no quartz surfaces are available for further cementation.

Computed mineral abundances are used to compute $\bar{s}_{0,M}$ through a fit of the measured permeabilities of the Garn Formation sandstones reported by Ehrenberg (1990). The results of preliminary regressions are shown in Fig. 2 and was performed in two steps. The first step is to fit data obtained at depths shallower than that of the onset of illitization assuming $\bar{s}_{0,M}$ is identical for all of the minerals present in the sandstone. This results in $\bar{s}_{0,M} = 170 \text{ cm}^{-1}$ and is illustrated by the solid curve. The second step is the regression of the permeability data at greater depths to obtain the $\bar{s}_{0,M}$ value for illite, which is dramatically larger than that of the other minerals due to its fibrous texture. A value of $\bar{s}_{0,illite} = 18000 \text{ cm}^{-1}$ leads to the fit illustrated in Fig. 2 is the result of regression calculations, these $\bar{s}_{0,M}$ values permit permeability predictions of sandstones with significantly different initial mineral abundances and temperature/depth evolutions.