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Review

The influence of clay mineralogy on formation damage in North Sea reservoir sandstones: A review with illustrative examples

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ABSTRACT

This paper critically reviews the clay mineralogy of reservoir sandstones in the North Sea, as assessed from peer-reviewed papers in the literature as well as from the authors' personal experience, in the particular context of formation damage. The most common clay minerals in these sandstones are well-crystallized kaolinite, mainly occurring as pore-filling vermiform and booklet-like aggregates, illitic clays, usually in the form of pore-filling networks of thin lath-like, filamentous or hairy particles, but less frequently as platy aggregates, and chlorite, most commonly found as pore-lining aggregates of interlocking, well-developed, bladed crystals. All these clay minerals are authigenic (diagenetic) in origin. Discrete smectite is rarely found in North Sea reservoir sandstones, even though associated pelitic rocks may contain an abundance of this type of clay mineral.

The crystallization of kaolinite in these sandstones has been attributed to a variety of stages in the paragenetic sequence, particularly in relation to the authigenic formation of calcite and quartz. However, most evidence suggests that vermiform kaolinite is a product of early diagenesis at temperatures ranging from surface to 40 °C, either before or contemporaneously with carbonate cementation and before the formation of quartz overgrowths. Exceptions to this generalization may occur because of complex basin histories involving tectonic uplift and migration of fluids of varying chemistry. With increasing depth of burial and at higher temperatures, the kaolinite in these reservoir sandstones converts at least partially to dickite, which occurs in more blocky aggregates. Consideration of recent theoretical studies of kaolinite indicate that at pH values >8 all face and edge surfaces will be uniformly negatively charged, strongly suggesting that in these circumstances the kaolinite will become disaggregated to form stable dispersions capable of migration where there is sufficient force of hydrodynamic flow.

The illitic clay in North Sea reservoir sandstones is usually described in terms of two discrete phases, namely illite itself and mixed-layer illite–smectite (I/S). Evidence is presented to show that in all probability only one illitic phase exists in these sandstones and that the mixed-layer phase in reality consists only of very thin illite (<5 nm in thickness). Such material when sedimented on glass slides adsorbs ethylene glycol between its thin particles and yields an XRD pattern identical to that of I/S, usually of a regularly ordered (R_3) form. In this case, however, diffraction is an interparticle phenomenon and the "smectite" layers detected are more apparent than real. In the North Sea reservoir sandstones, illitic material is considered to exist in both pore-filling and pore-lining modes, with the latter forming at low temperatures very early in the paragenetic sequence, perhaps even in equilibrium with depositional pore waters. In contrast, the pore-filling illitic clay is thought to have formed at higher temperatures, in excess of 100 °C, following deeper burial. In this paper, it is argued that so-called pore-lining illite is sometimes an artefact of the customary drying procedure of the sandstone samples prior to examination by SEM or optical microscopy. Such procedures cause some or all of the delicate pore-filling illite filaments to shrink back against the pore walls so producing the appearance of a pore-lining mode. Evidence against a separate early phase of illite formation in pore-lining mode includes K–Ar dating showing that the age of North Sea illites is always much later than the stratigraphic age of the sediment, oxygen isotope evidence showing that North Sea illites have usually formed at relatively high temperatures (>100 °C), SEM observations showing that putative pore-lining illite actually consists of dense masses of compacted illite fibres identical to those that fill pores, and finally the similar chemical compositions of both pore-lining and pore-filling illite showing them both to be of a muscovitic or phengitic nature. It is probable that the illitic clay in North Sea reservoir sandstones is highly dispersible and is prone to redistribution, particularly in the Na^+-

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saturated state, and because of its very fine particulate form would therefore be readily mobilized by hydrodynamic forces.
Finally, several illustrative examples are presented to show that clay migration during fluid injection is a probable cause of formation damage in North Sea reservoir sandstones. SEM observations following fluid treatments clearly show the breakup of kaolinite aggregates whereas the evidence for illite mobilization consists of the appearance of large holes in the network of pore-filling illite laths. In addition to this, analytical evidence shows that both kaolinite and illite particles have exited core samples following fluid or gas flow, thereby proving their mobility within the core.

Contents

1. Introduction

Formation damage has been described as any alteration of the hydrocarbon reservoir rock following various wellbore operations, which may be irreversible and which may have a serious economic impact upon the productivity of the reservoir. In the oil industry, it has been realized that formation damage may occur at any stage of the production process, including drilling, completion, injection, attempted stimulation or production of the well. It is a problem of immense economic significance to the oil industry, literally costing billions of dollars, with one recent estimate putting the cost as high as 140 billion dollars per annum (Byrne, private communication).

Although there are many types of formation damage unconnected with clay mineralogy (Krueger, 1986), the migration of fine particles, which usually consist principally of clay minerals, is often considered as a major cause. These clay minerals migrate as a consequence of physical and/or chemical reactions (*e.g.* dispersion of minerals following chemical reactions with formation fluids), so that fines physically break away during hydrodynamic flow. Eventually migration of those minerals may cause accumulation in pore throats, block fluid flow and thus reduce overall permeability. Wilson et al. (2014) reviewed the role of individual clay minerals in causing formation damage through fines migration and concluded that kaolinite and illite, including mixed-layer illite/smectite (I/S), were the major culprits in this respect. Chlorite typically occurs in aggregates of large interlocking particles and was not thought to be susceptible to dispersion and migration. The role of smectite was considered to be uncertain in that it could under certain circumstances swell to a gel-like form thus blocking fluid flow *in situ*, although molecular dynamics simulation studies suggest that this would be unlikely under basin conditions (Odriozola et al., 2004; De Pablo et al., 2005), or it could disperse into fine particles and migrate in the same way as kaolinite and illite.

There is a plethora of opinions as to how clay minerals have formed within the reservoir sandstones of the North Sea, in particular the physicochemical conditions of their formation, the time at which their crystallization occurred, the role (if any) of precursor minerals, and their relationship with the authigenic growth of non-clay minerals. The latter factor is particularly important in the context of the present paper as it bears on the question of whether the clay particles are free to disperse and migrate. For example, early SEM observations of the Magnus Sandstone in the North Sea showed that filamentous illitic material was literally anchored within quartz overgrowths strongly suggesting in this particular case that particle dispersion would be extremely difficult (McHardy et al., 1982).

The aim of this paper, therefore, is to review the clay minerals found in North Sea reservoir sandstones of a variety of ages, from the particular perspective of their nature and most importantly their ability to disperse in various fluids and their potential to cause significant formation damage. Such damage will be exemplified by a number of illustrative case studies.

2. Review of clay mineralogy of North Sea reservoir sandstones

2.1. Introduction

It is remarkable that the clay mineralogy of North Sea reservoir sandstones of Mesozoic and Upper Palaeozoic ages is usually dominated only by kaolinitic and illitic clays. This is certainly true of reservoir sandstones of Jurassic age (Wilkinson et al., 2006) even though the associated pelitic rocks in the stratigraphic sequence may contain an abundance of swelling clays (Jeans, 2006a). A kaolinite–illite assemblage is also abundant in the clay fractions of reservoir rocks of Permian age in shelf areas, although a chlorite–illite assemblage dominates reservoir rocks in deep basinal areas (Ziegler, 2006). The clay mineralogy of associated pelitic rocks is also often dominated by a chlorite–mica assemblage and sometimes by smectitic clays, with kaolinite occurring relatively rarely (Jeans, 2006b). A kaolinite–illite assemblage dominates the clay mineralogy of most reservoir sandstones of Carboniferous age