Marine and Petroleum Geology 77 (2016) 703–713

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Compaction of diagenetically altered mudstones – Part 1: Mechanical and chemical contributions

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A R T I C L E I N F O

Article history:
Received 26 May 2016
Received in revised form
7 July 2016
Accepted 18 July 2016
Available online 19 July 2016

Keywords:
Mudstone
Clay diagenesis
Chemical compaction
Mechanical compaction
Overpressure
Effective stress

A B S T R A C T

At low temperatures, siliciclastic mudstones compact mechanically. Above 70 °C, where the smectite-to-illite transformation dominates clay diagenesis, they also compact chemically, provided that excess pore water can escape. There are two prevailing conceptual models for the compaction of siliciclastic mudstones at higher temperatures, above ~100 °C. One holds that precipitation of minerals during diagenesis cements the mudstones such that mechanical compaction no longer occurs even if the mudstones can drain freely. According to the other model, diagenetically altered mudstones continue to compact mechanically in response to increasing effective stress. We found that wireline-log and pressure data from Cretaceous mudstones at Haltenbanken are consistent with ongoing mechanical compaction accompanying chemical compaction up to at least 130 °C. We suggest that mechanical compaction continues because grain contacts in siliciclastic mudstones following smectite-to-illite transformation are still mostly between clay grains.

1. Introduction

Muds and mudstones are the world's most common sediment type (Schieber, 1998). Knowledge of their compaction behaviour is essential for pre-drill pore pressure estimation from basin modelling and seismic velocities. Relationships between wireline log responses and effective stress are also required for estimating pore pressure while drilling through mudstone formations, to anticipate the pore pressures that will be encountered when the drill-bit encounters permeable reservoir formations. These two articles on compaction and overpressure in diagenetically altered mudstones are directed towards improved pore pressure estimation using wireline logs in mudstones at the temperatures where clay diagenesis takes place. Here, in Part 1, we discriminate between two alternative hypotheses concerning compaction processes in diagenetically altered mudstones, and in Part 2 (Goulty and Sargent, 2016) the implications for pore pressure estimation are explained.

In the conversion of muds to mudstones during burial, mechanical compaction dominates initially, with grains becoming more closely packed together through slippage, rotation and breakage. Provided that potassium is available, commonly sourced by the dissolution of potassium feldspar, transformation of smectite to illite starts at around 65–70 °C and is the principal clay diagenetic change in mudstones up to ~120 °C. The reaction pathways release water, silica and cations that can react with kaolinite and calcite to produce chlorite and ankerite (Boles and Franks, 1979). In addition, most detrital plagioclase becomes albitized as a result of reacting with sodium ions released from the transforming smectite (Milliken, 1992). When mudstones have attained a temperature of ~120 °C through burial, the proportion of expandable 'smectitic' interlayers containing hydrated cations in mixed-layer illite/smectite crystals has generally reduced to about 20% with all the smectite 2:1 layers having dissolved, so that the remaining expandable interlayers separate illite fundamental particles (Środoń et al., 2000). Details of other diagenetic reactions that take place in mudstones in the temperature range 70–120 °C are given by Hower et al. (1976), Freed and Peacor (1989), Bjørlykke (1998), Nadeau et al. (2002), Nadeau (2011) and Thyberg and Jahren (2011). Above 120 °C, kaolinite starts to transform to illite, provided that potassium is still available, with further release of water (Giorgetti et al., 2000; Nadeau et al., 2002).

According to Bjørlykke and Høeg (1997), compaction of mudstones at depths greater than 2–3 km is mainly chemical, involving dissolution and precipitation of minerals, and Bjørlykke (1998) stated that mudstones with overpressures at depths where chemical compaction is dominant (>2–3 km depth, > 70–100 °C) should not be expected to have significantly higher porosity than normally

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http://dx.doi.org/10.1016/j.marpetgeo.2016.07.015

pressured rocks. Their conceptual model is summarized on the left side of Fig. 1. Following the initial stage where mechanical compaction dominates, there is a transitional stage in which chemical compaction due to clay diagenesis has started and mechanical compaction continues. Chemical compaction dominates at higher temperatures, and by implication proceeds independently of effective stress.

An alternative conceptual model for the compaction of diagenetically altered mudstones was set out by Dutta (2002), who had previously modelled mudstone compaction and overpressure generation with the inclusion of reaction kinetics for the transformation of smectite to illite (Dutta, 1986). A key aspect of the model is the suggestion by Lahann (2002) that the normal compaction trend for a mudstone is bounded by distinct compaction profiles for smectite-rich mudstone and illite-rich mudstone, before and after the main phase of smectite-to-illite transformation. In this model, which is summarized on the right side of Fig. 1, the porosity of diagenetically altered mudstones depends on both effective stress and temperature history, and there is no suggestion that mechanical compaction becomes negligible at temperatures above ~100 °C.

We have investigated Cretaceous mudstones in the Haltenbanken area, offshore mid-Norway (Fig. 2) at depths where temperatures are in the range 70–170 °C. The sparse pressure data available in the Cretaceous formations show that the mudstones are overpressured with a fairly consistent pore pressure–depth profile across the area (O'Connor et al., 2012). We found large differences between compaction profiles and concluded that the vertical effective stress history was the principal factor responsible for the differences, even though the vertical effective stress shows little spatial variation at the present day (Cicchino et al., 2015). Sargent et al. (2015) analysed density and sonic logs together to show how the amount of overpressure due to unloading processes can be estimated from these logs.

Here we use the wireline-log and pressure data in Cretaceous mudstones at Haltenbanken to discriminate between the two conceptual models for mudstone compaction. Our results are consistent with the idea that mechanical compaction continues to occur in diagenetically altered mudstones subject to increasing effective stress; the results falsify the hypothesis that porosity in mudstones undergoing diagenesis at temperatures above 100 °C is a function only of chemical processes and independent of effective stress.

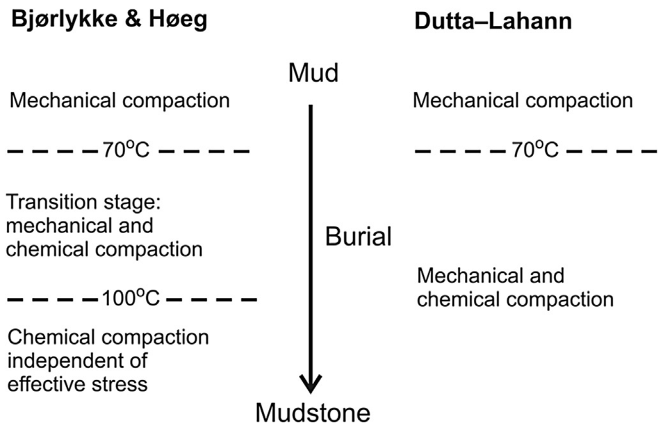

Fig. 1. Alternative conceptual models for the compaction of mudstones. Left: the model of Bjørlykke and Høeg (1997) and Bjørlykke (1998), in which mudstones at temperatures above ~100 °C compact chemically, independent of effective stress. Right: the model of Dutta (2002) and Lahann (2002) in which mechanical compaction continues together with chemical compaction in diagenetically altered mudstones.

2. Compaction profiles for Cretaceous mudstones at Haltenbanken

Within Cretaceous mudstones in the Haltenbanken area, offshore mid-Norway, Cicchino et al. (2015) found substantial lateral variations in porosity, contoured in Fig. 2b, in spite of the fact that the pressure–depth profile within the Cretaceous formations is fairly consistent across the area (Fig. 3). In this section, we summarize the geological background, the interpreted pore pressure history, and the density data from which mudstone porosity was inferred.

2.1. Geological background

The Halten Terrace (Fig. 4) is a structure that developed during a Jurassic–Early Cretaceous rift episode, bounded by the Klakk and Bremstein fault complexes (Blystad et al., 1995). The Cretaceous post-rift sediments are dominated by the mudstone lithology of the relatively deep marine palaeo-environment. Mudstones of the Lange Formation dominate the Lower Cretaceous succession and extend upwards into the Upper Cretaceous, where they are overlain by the clay-rich Kvitnos Formation (Dalland et al., 1988). The Lange and Kvitnos formations form the study interval, with a combined thickness that comprises about 75% of the Cretaceous strata in the area. The Lange Formation has a maximum recorded thickness of about 1300 m at Haltenbanken. There are a few stringers of limestone in the lower part of the formation and several sandstone turbidite bodies, generally isolated and encased in mudstone, in the upper part. These turbidites include the Lysing Formation where some of the pressure measurements (Fig. 3) were made, which is coeval with the youngest Lange mudstones. The Kvitnos Formation is around 500 m thick and predominantly consists of claystones, interbedded with stringers of carbonate and sandstone.

The Kvitnos Formation is overlain by around 1200 m thickness of Upper Cretaceous, Palaeogene and Neogene claystone formations, terminating at an unconformity that developed during the late Pliocene (Dalland et al., 1988; Blystad et al., 1995). Between 2.8 Ma and the present, following the late Pliocene hiatus, glaciogenic sediments of the Naust Formation have been deposited in a series of east-to-west prograding wedges (Rise et al., 2005, 2006; Ottesen et al., 2009; Dowdeswell et al., 2010). Their thickness ranges up to 1300 m in the study area, so the deposition rate was much more rapid after 2.8 Ma than at any earlier time during the Cenozoic era (Fig. 4).

2.2. Pore pressure history and density logs

During mechanical compaction, increasing effective stress pushes the grains closer together as water escapes from the pore space, reducing porosity and permeability. When water cannot escape fast enough to remain in hydrostatic equilibrium as burial proceeds, overpressure is said to be generated by disequilibrium compaction. The retention of excess water necessarily means that the porosity is greater than it would be if the pore water were in hydrostatic equilibrium. Clay diagenesis can also generate overpressure. Illitization of smectite produces some water and makes a mudstone more compactable, so its density becomes greater at constant effective stress (Lahann, 2002). Again, overpressure is generated if pore water cannot escape fast enough to remain in hydrostatic equilibrium. A significant difference between disequilibrium compaction and clay diagenesis as mechanisms of overpressure generation is that clay diagenesis may increase the pore pressure sufficiently to reduce the effective stress acting on the mudstone, in which case the mudstone is said to be unloaded. Disequilibrium compaction acting alone in a mudstone bed cannot