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Research paper

Compaction of diagenetically altered mudstones – Part 2: Implications for pore pressure estimation

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ABSTRACT

Diagenetically altered mudstones compact mechanically and chemically. Consequently, their normal compaction trends depend upon their temperature history as well as on the maximum effective stress they have experienced. A further complication is that mudstones are commonly overpressured where clay diagenesis occurs, preventing direct observation of the hydrostatic normal compaction trend. A popular way to estimate pore pressure in these circumstances is to calculate the sonic normal compaction trend in a well with a known pressure–depth profile by applying Eaton's method in reverse, and then to estimate pore pressure in offset wells using Eaton's method conventionally. We tested this procedure for Cretaceous mudstones at Haltenbanken. The results were inconsistent because the sonic log responds differently to disequilibrium compaction overpressure and unloading overpressure, and their relative contributions vary across the basin. In theory, a two-step method using the density and sonic logs could estimate the contributions to overpressure from disequilibrium compaction and unloading. The normal compaction trend for density should be the normal compaction trend at the maximum effective stress the mudstones have experienced, not at hydrostatic effective stress. We advocate the Budge-Fudge approach as a starting point for pore pressure estimation in diagenetically altered mudstones, a two-step method that requires geological input to help estimate the overpressure contribution from disequilibrium compaction. In principle, the Budge-Fudge approach could be used to estimate the normal compaction trend for mudstones at the maximum effective stress they have experienced, and so form the basis of the full two-step method through the use of offset wells. Our initial efforts to implement the full two-step method in this way at Haltenbanken produced inconsistent results with fluctuations in estimated pore pressure reflecting some of the fluctuations in the density logs. We suspect that variations in the mineralogical composition of the mudstones are responsible.

1. Introduction

This article and its companion article, Part 1 (Goulty et al., 2016), are directed towards improved pore pressure estimation using wireline logs in mudstones at the temperatures where clay diagenesis takes place. In Part 1, we show that mechanical and chemical compaction have both continued to take place in Cretaceous mudstones at Haltenbanken, offshore mid-Norway up to temperatures of at least 130 °C. In this article, we examine the implications for pore pressure estimation.

A description of the geology is given in Part 1, based on the work of Blystad et al. (1995) and Dalland et al. (1988). Here we repeat only the key points. Following a Jurassic–Early Jurassic rift episode, the Cretaceous post-rift sediments at Haltenbanken were deposited in a moderately deepwater marine environment. The Lower Cretaceous Lange Formation and the overlying Upper Cretaceous Kvitnos Formation comprise our study interval, and have a combined thickness of up to 1800 m. Their lithology is mainly mudstone, although there are several isolated sandstone turbidites in the upper part of the Lange Formation. They are overlain by around 1200 m thickness of Upper Cretaceous–Neogene claystone formations, terminating at an unconformity that developed during the late Pliocene. Since 2.8 Ma, following the late Pliocene hiatus, burial has been rapid as glaciogenic sediments of the Naust Formation were deposited with thickness ranging up to 1300 m in the study area (Rise et al., 2005).

The Cretaceous mudstones in the Haltenbanken area lie at depths where temperatures are in the range 70–170 °C. The sparse

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pressure data available in the Cretaceous formations show that the pore pressure–depth profile is fairly consistent across the area (O'Connor et al., 2012), yet Cicchino et al. (2015) found wide differences in porosity between wells (Fig. 1). In Part 1, we analysed density and sonic logs to show that the effective stress history is the principal factor responsible for the porosity differences: at the same depth, the lower porosity mudstones in the northeast of the study area have experienced more mechanical compaction than the higher porosity mudstones in the southwest.

Here we introduce for diagenetically altered mudstones the concept of a normal compaction surface on a 3-D plot of vertical effective stress against sonic transit time and density, and point out that there is a corresponding unloading volume in this 3-D space. This plot helps us to visualize why the vertical effective stress is not uniquely defined by density and sonic transit time in diagenetically altered mudstones, even if their depositional lithology is known and they have been uniaxially consolidated. We then compare pore pressure estimates from wireline logs in the Cretaceous mudstones at Haltenbanken obtained by the widely used method of Eaton (1975) and the Budge-Fudge approach proposed by Sargent et al. (2015). We argue that the Budge-Fudge approach is preferable because it requires explicit accounting for both disequilibrium compaction and unloading mechanisms of overpressure generation, although it does require geological input to help estimate the overpressure contribution from disequilibrium compaction. In principle, it should be possible to apply the Budge-Fudge approach in offset wells to provide the basis for a full two-step method of pore pressure estimation using density and sonic logs in a subject well.

2. Normal compaction surface and unloading volume

Normal compaction behaviour describes the porosity response of clastic sediment to increasing effective stress, without restriction to circumstances where the pore pressure remains hydrostatic. Commonly, only vertical effective stress is considered because it is relatively easy to determine, by integrating the density log. This simplification is valid for 1-D compaction or, more generally, in

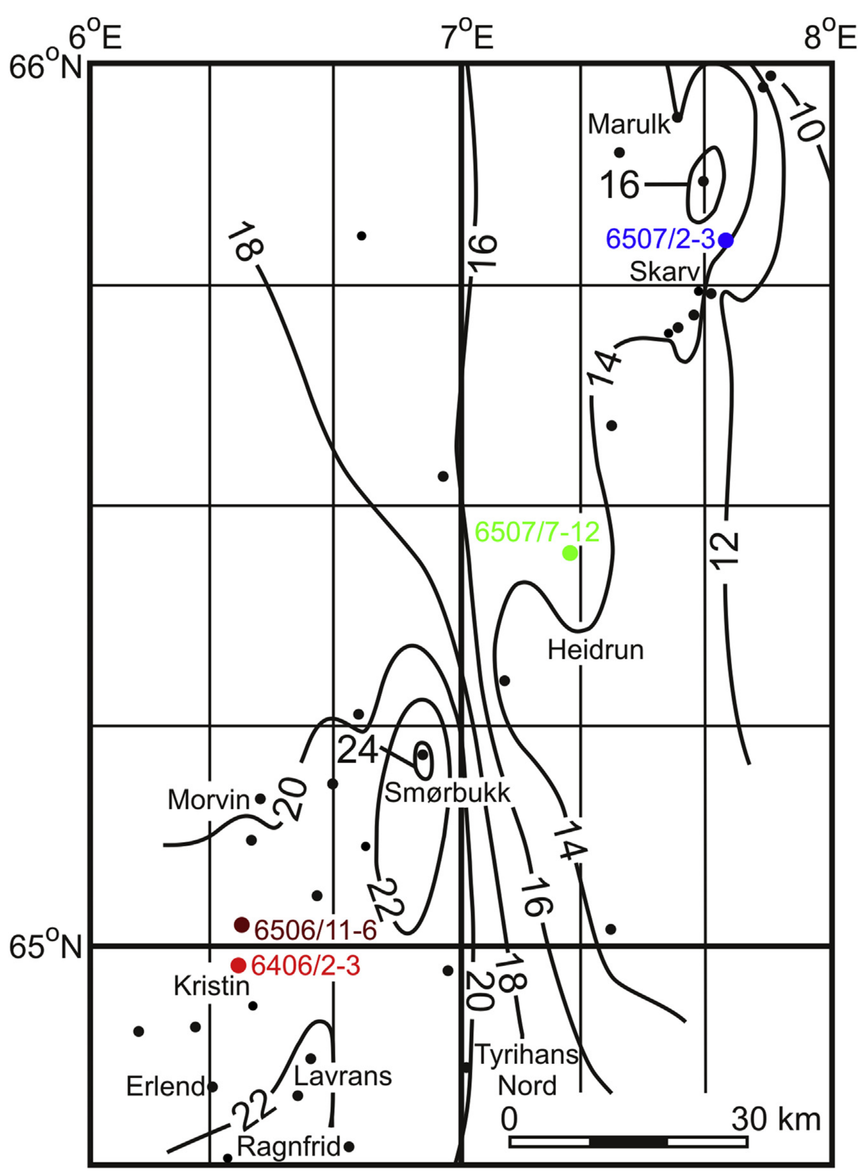

Fig. 1. Map of the study area with contours of the density log porosity values (%) on the best-fitting exponential trends for the Cretaceous Kvitnos and Lange mudstones at 2700 m depth below seafloor.