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Research paper

Constraining sub-seismic deep-water stratal elements with electrofacies analysis; A case study from the Upper Cretaceous of the Måløy Slope, offshore Norway

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A B S T R A C T

Electrofacies represent rock facies identified from wireline-log measurements, and allow extrapolation of petrophysical characteristics away from stratigraphic intervals that are calibrated to core. This approach has been employed to reduce uncertainty in the identification of the sub-seismic depositional elements in the late Cenomanian–Coniacian succession of the northern Måløy Slope, offshore Norway. Core logging permits identification of eleven distinct sedimentary facies that are grouped into four facies associations: FA A-turbidite sandstones, FA B-heterolithic siltstones and sandstones, FA C-debrites and FA D-slide and slump deposits. Each facies association is defined by a distinct combination of petrophysical characteristics, including porosity, density, gamma-ray, sonic and resistivity. Using neural network analysis, electrofacies are calibrated with sedimentary facies, thereby allowing us to map their thickness and stacking patterns within the studied deep-water succession. We demonstrate that this approach is particularly useful where the presence of glauconite makes the distinction between sandstone- from shale-rich units difficult using gamma-ray logs alone. Our results indicate that the succession of interest is dominated by debris flows and slide and slump deposits, which are commonly poorly imaged on seismic reflection datasets in the northern North Sea. The methodology presented here can aid the correlation of deep-water stratal elements at production and exploration scales in stratigraphic successions that have undergone similar burial histories.Furthermore, this method may help in the identification of mass flow deposits that are present in Upper Cretaceous deep-water systems of the North Sea.

1. Introduction

In the northern North Sea, deep-water systems have been widely studied because they represent potentially large oil and gas reservoirs and are therefore economically important (e.g. Johnson and Stewart, 1985; Løseth et al., 2009; Stow and Mayall, 2000; Ziegler, 1977). Deep-water sandstone reservoirs contain a variety of architectural elements, but are dominated by channel-fill, sheet and thin-bedded levee deposits (e.g. Lawrence and Bosman-Smits, 2000). In contrast, mass transport deposits (including debrites, slides and slumps) are not regarded as reservoirs, because of the lack of vertical and horizontal connectivity between sandbodies that are typically contained as isolated clasts in a muddy matrix (Bull et al., 2009; Weimer and Shipp, 2004). Shanmugam et al. (1994, 1996) used ~3700 m of core to illustrate that most Cenozoic-Tertiary basin-floor fans of the North Sea are dominated by relatively muddy slump and debris flow deposits, rather than sandstone-rich turbidites. However, this interpretation was challenged by Hiscott et al. (1996), who argued that the criteria used by Shanmugam et al. (1994, 1996) to differentiate between classic turbidites and mass flow deposits (e.g. grading, sorting, sedimentary structures) were flawed. This dispute highlights the need to develop new workflows to better constrain the sub-seismic elements that comprise deep-water successions in subsurface datasets, especially where core data are lacking.

The depositional architecture of deep-water systems results from the interplay of autogenic (such as depositional relief and

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system avulsion) and allogenic controls (such as the tectonic setting, sediment provenance and eustasy) (Calvache et al., 1997; Martinsen et al., 2005). To help us better understand the stratigraphic architecture of deep-water reservoirs, seismic reflection and well data need to be integrated. Seismic data can provide information on the basinal context and large-scale morphology of a deep-water depositional system, whereas well data allows us to determine the vertical distribution of sandstone from logging tools such as gamma-ray, density and neutron porosity. The presence of some cements and minerals, for example glauconite, can influence the response of the logging tools within the formation and make the distinction between sand-rich (reservoir) intervals and claystone-rich (non-reservoir) intervals equivocal (McRae, 1972; Rider and Kennedy, 2011). The current study proposes a methodology based on neural network analysis. Neural network analysis uses the petrophysical signature of pre-defined rock unit (here sedimentary facies associations) to generate electrofacies and extrapolate their distribution away from the cored sections of the well.

The aims of this study are: 1) to describe and interpret the core-based sedimentology of 125 m of core from a 600 m thick deep-water succession preserved on the northern Måløy Slope, offshore Norway (wells 6204/10-1, 6204/10-2A, 6204/10-2R, 6204/11-1, Fig. 1); 2) to calibrate electrofacies logs with core data and extrapolate facies associations defined away from cored intervals; 3) to test how far, geographically and stratigraphically, core-calibrated electrofacies logs can be extrapolated away from the study interval; and 4) to establish the proportion and distribution of mass flow deposits within the Upper Cretaceous succession of the northern Måløy Slope, with the aim of determining their significance in terms of basin margin evolution. The methodology developed is then tested on the same deep-water succession on an offset well (35/9-3T2), which is located ~50 km south of the study area. In this well, a core and a similar set of well data are available, thus allowing a far-field test of the reliability of electrofacies analysis at predicting facies associations. The application of electrofacies analysis is especially valuable in the studied succession because the seismic data quality is variable, and the presence of authigenic and detrital glauconite means it is difficult to use individual tools, especially gamma-ray, to discriminate between reservoir sandstone and non-reservoir mudstone.

2. Study area

2.1. Tectono-stratigraphic evolution of the northern Måløy Slope

The Måløy Slope is bounded to the west by large (>5 km displacement), west-dipping normal fault complexes that form the eastern margin of the Sogn Graben, and to the east by the Øygarden Fault Complex. The study area includes the Selje High, a ~30 km long NE–SW-trending, Cretaceous structure (Fig. 1). Rifting and formation of normal fault blocks in the Middle to Late Jurassic was superseded by thermally-driven, post-rift subsidence in the Cretaceous and Tertiary, and the formation of a deep-water basin (Surlyk et al., 2003) (Fig. 2). Syn-rift relief was infilled and draped by Upper Cretaceous to lower Palaeogene post-rift deposits (Surlyk et al., 2003).

2.2. Upper Cretaceous stratigraphic framework

The study interval is located in the Upper Cretaceous Shetland Group (Fig. 3), which is well-developed in the graben areas (e.g. Sogn Graben), where it is up to 2 km thick, and pinches out towards the eastern basin-margin (Surlyk et al., 2003). It can be subdivided into five siliciclastic-dominated formations, which are, in stratigraphic order, the Svarte, Blodøks, Tryggvason, Kyrre, and Jorsalfare formations (Deegan and Scull, 1977) (Fig. 3).

In the southern part of the northern North Sea, the Cenomanian succession (Svarte Formation) consists of calcareous mudstone interbedded with chalky limestones. The proportion of limestone gradually decreases northwards towards the Måløy Slope and away from syn-depositional structural highs over which the formation is thin or absent (Surlyk et al., 2003). The Turonian succession (Tryggvason Formation) is lithologically similar to the Cenomanian

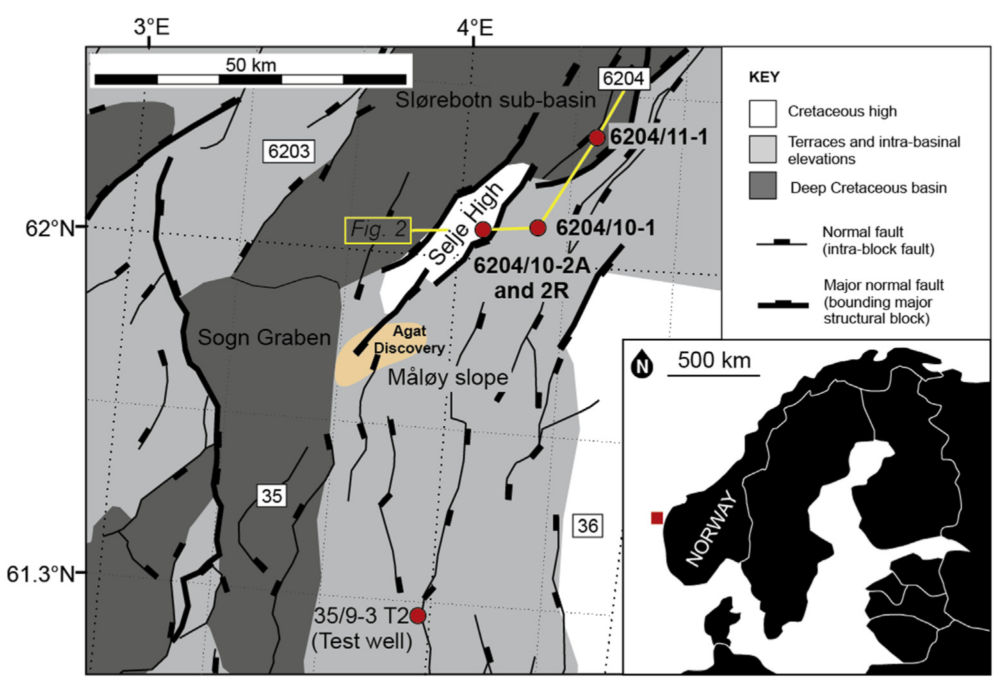

Figure 1. Location map of the study area with inset map showing the location of the study area in relation to Norway. Wellbores 6204/10-2A and 2R are located on the western flank of the Selje High. The location of the Agat discovery is indicated (after Skibeli et al., 1995).