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Comparison of deeply buried paleoregolith profiles, Norwegian North Sea, with outcrops from southern Sweden and Georgia, USA — Implications for petroleum exploration

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ABSTRACT

For the first time on the Norwegian Continental Shelf, deeply buried paleoregolith profiles have been identified as part of the petroleum reservoirs in recently discovered oil fields on the Utsira High, Norwegian North Sea. Reservoir properties (porosity and permeability) in the granitic basement on the Utsira High are mainly the result of physical and chemical alteration of the rock occurring in the near-surface environment during sub-aerial exposure of the high in the Mesozoic. Evaluating the reservoir potential of altered basement rocks requires a different approach than in conventional petroleum exploration. In this paper, macroscopic, mineralogical and micromorphological alteration features observed in two deeply buried paleoregolith profiles are compared with surface paleoregoliths from Ivö Klack, Sweden and Georgia, USA. The paleoregolith profiles are subdivided into specific weathering facies (altered coherent rock facies, saprock facies and saprolite facies) based on the rock fabric and mechanical strength. The reservoir potential of each weathering facies is controlled by the type and degree of alteration. In the altered coherent rock facies, porosity and permeability is mainly controlled by joints and microfractures that developed prior to subaerial exposure of the granitic pluton. In the saprock facies, intensified chemical dissolution of plagioclase enhanced porosity and the development of mesofractures improved the connectivity between pores. In the saprolite facies, progressive dissolution of plagioclase creates porosity, but the precipitation of clays within voids and mesofractures has a destructive effect on the overall reservoir properties. The deeply buried paleoregolith profiles from the Utsira High display comparable macroscopic, mineralogical and micromorphological alteration features to what was observed in surface paleoregoliths from Ivö Klack and Georgia. Outcrop studies may therefore be an important tool when evaluating the reservoir potential in subsurface paleoregoliths.

1. Introduction

On the Utsira High, Norwegian North Sea (Fig. 1A) hydrocarbon reservoirs were recently discovered in deeply buried paleoregolith profiles (Riber et al., 2015; Sørlie et al., 2014, 2016). The discovery represents the first time altered and fractured basement rocks are identified as petroleum reservoirs on the Norwegian Continental Shelf. The present paper extends two previous studies from the area (Riber et al., 2015, 2016). By comparing deeply buried paleoregoliths from the Utsira High with outcrops from Georgia, USA (Fig. 2A) and Ivö Klack, Sweden (Fig. 2B), this study will attempt to evaluate how physiochemical alteration in the Critical Zone affected the reservoir quality in the granitic basement rocks on the Utsira High.

Studies of outcrops are common and often needed when constructing subsurface models of conventional siliciclastic and bioclastic petroleum reservoirs (Grammer et al., 2004) as drill cores are normally far between and only provide limited three-dimensional resolution. Suitable outcrops for comparison were identified from Georgia, USA (Fig. 2A), Ivö Klack, Sweden (Fig. 2B), and Bornholm, Denmark (Fig. 2B). The present paper will compare the results from the Utsira High with the results from Georgia and Ivö Klack, while comparable results from Bornholm, Denmark are presented in an accompanying paper (Tan et al., 2017). Recent H-O isotope studies from kaolins in the Cenozoic weathering sections from Georgia, USA and the Mesozoic weathering sections from Ivö Klack and Bornholm, suggests subaerial formation under humid and subtropical conditions (Gilg et al., 2013), that may

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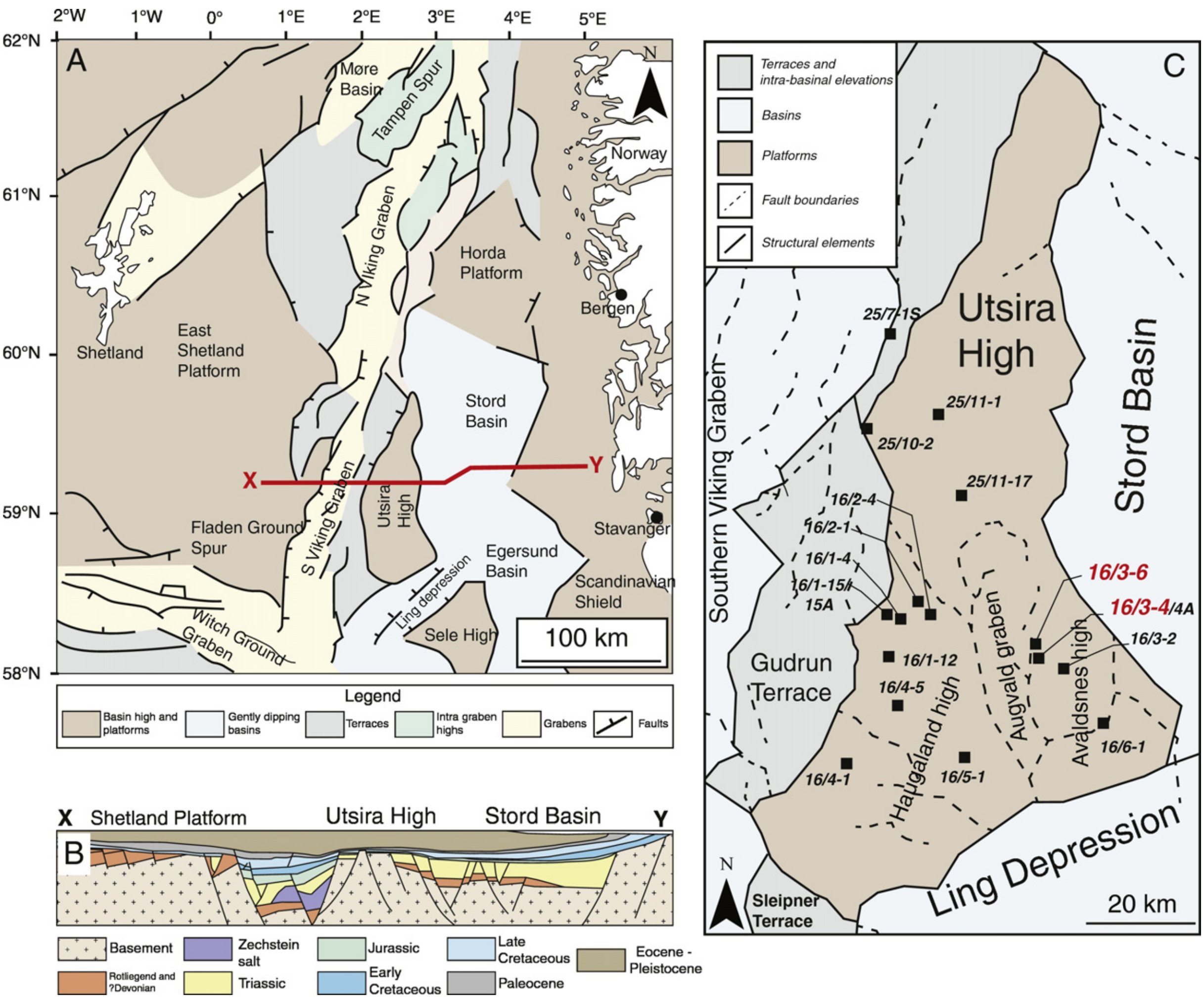

Fig. 1. A) Regional map of the North Sea area (modified from Gregersen et al., 1997) with cross-section marked X-Y. B) Cross-section (X-Y) of the South Viking Graben (modified from Ziegler, 1992). C) Map showing major structural elements on the Utsira High and location of eighteen wells penetrating basement rocks. The two wells included in this study (16/3-4 and 16/3-6) in red.

have been comparable to Mesozoic northern North Sea climatic conditions (Lidmar-Bergström, 1982; Hallam et al., 1993; Abbink et al., 2001; Vajda and Wigforss-Lange, 2009; Nystuen et al., 2014).

In the first comprehensive study of altered basement rocks on the Norwegian Continental shelf, Riber et al. (2015) found that reservoir quality in crystalline rocks from 18 different wells on the Utsira High (Fig. 1C) varied greatly as a function of type and degree of alteration. Based on detailed clay mineralogical, petrographical and geochemical studies Riber et al. (2016) discussed alteration features resulting from near-surface processes in two-well developed paleoregolith profiles (wells 16/1-15 and 16/3-4) (Fig. 1C). The minimal postweathering alteration (diagenetic reactions) observed in the paleoregolith profile in well 16/3-4 (Riber et al., 2016) makes the paleoregolith profile from this well suitable for comparison with a deeply buried paleoregolith profile in well 16/3-6 (Fig. 1C) located about 1 km north of 16/3-4, and surface paleoregolith profiles from Georgia, USA (Fig. 2A) and Ivö Klack, southern Sweden (Fig. 2B).

The coupled near-surface interactions of biochemical and physical processes in the Critical Zone are responsible for the alteration of solid rock to regolith (weathering profile) and soil (Brantley et al., 2006, 2007; Buss et al., 2008; Lin, 2010). Generally a regolith may be divided into three weathering facies based on the degree of recognizable primary rock structures and the mechanical rock strength: the altered coherent rock facies, saprock facies, and saprolite facies (Velde and Meunier, 2008). When considering the regolith as a medium through which fluids can migrate and be stored, the recognition of weathering facies is of great importance as each facies displays contrasting hydraulic properties (porosity and permeability) (O'Brien and Buol, 1984; Acworth, 1987; Schoeneberger and Amoozegar, 1990; Wright and Burgess, 1992; Driese et al., 2001; Négrel, 2006; Velde and Meunier, 2008; Pagliai and Kutilek, 2008; Zauyah et al., 2010). The porosity and permeability in the weathered rock are mostly controlled by fractures and voids. Fractures are particularly important as pathways for the ingress of formation waters and the voids are created from the dissolution of labile minerals and become more important with progressive chemical attack (Acworth, 1987; Wright, 1992; Nelson, 2001; Velde and Meunier, 2008; Zauyah et al., 2010; Jin et al., 2011; Borrelli et al., 2012; Bazilevskaya et al., 2013). With advanced chemical weathering, the neoformation of phyllosilicates and hydroxides will clog previously formed voids and fractures and hence have a negative impact on reservoir quality (Acworth, 1987; Driese et al., 2001; Meunier, 2005; Pagliai and Kutilek, 2008; Zauyah et al., 2010).

Most soils and regoliths are the products of multiple environments ranging over pedogenic time and may therefore be viewed as polygenetic (Molina et al., 1991; Richter and Yaalon, 2012). Furthermore, paleoregoliths are defined as weathering formations that were produced in a geomorphologic and/or climatic environment different from the present one (Battiau-Queney, 1996). In this context both the deeply buried weathering profiles from the Utsira High, and surface weathering sections from Georgia (Schroeder et al., 1997; Schroeder