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pT-effects of Pleistocene glacial periods on permafrost, gas hydrate stability zones and reservoir of the Mittelplate oil field, northern Germany

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During the past two million years low surface temperatures as well as episodically advancing ice sheets from Scandinavia acted on the subsurface pT-regime of northern Germany. Their likely effects on the petroleum system of Schleswig-Holstein were investigated. For the entire Quaternary mean annual ground temperature (MAGT) was reconstructed at a resolution of 1000 years by calibrating oxygen isotope records from ODP-site 659 to the climate of northern Germany of the past 120 kyr. The resulting MAGT trend served as input to an ice sheet model and a permafrost model along a 2D section crossing the petroleum bearing south-western part of Schleswig-Holstein. Here advances and retreats of the Scandinavian ice sheet during Saalian and Elsterian glaciation Stages were reconstructed. Maximum ice thicknesses of up to 1700 m and up to 20 periods of regional permafrost in northern Germany were reconstructed for the past 1.25 million years. Based on a basal heat flow of 50 mW/m^2 permafrost thicknesses exceeded 100 m during most of these periods, temporarily extending down to depths of more than 300 m. Favourable surface temperatures and long durations of cold periods provided favourable conditions for onshore gas hydrate stability zones at Mittelplate. Implementing these glacial dynamics into 2D basin modelling (PetroMod, IES, Aachen, Germany) of the Mittelplate oil field reveals five phases of gas hydrate stability at depths down to 750 m. The latest of these events occurred during the Weichselian about 20 kyr ago. The effect of the ice sheets on pore pressure in the subsurface strongly depends on the hydraulic boundary conditions at the ice base (e.g. frozen vs. temperate ice sheet base). Excess pore pressure in the reservoir of more than 10 MPa during ice overriding is possible and probable. The calculated temperature effect of the Pleistocene cooling on the Mittelplate reservoir is in the range of 3–7 °C. Even today temperature in the reservoir is still lowered by about 4 °C in comparison to pre-Pleistocene times. Despite the fact that a significant influence of glacial effects on petroleum generation can be ruled out at Mittelplate, we state that pT-effects in reservoirs related to glacial processes in formerly glaciated areas have been underestimated in the past.

1. Introduction

1.1. *The Quaternary of Schleswig-Holstein*

The Quaternary is characterized by global cooling and subdivided into cycles of colder glacial and warmer interglacial periods (e.g. Ehlers, 1994). During some glacial periods, ice sheets developed on the circum-polar landmasses of Scandinavia and spread over vast areas of northern Central Europe.

Studies on the number and the extent of ice sheets covering Schleswig-Holstein are mainly based on the interpretation of glacial landforms and/or the distribution of glacial deposits in northwest and central Germany. It was found that the first advance of the Scandinavian ice sheets across Schleswig-Holstein started about 350,000 years ago at the beginning of the Elsterian glaciation (e.g. Ehlers and Gibbard, 2003, 2004).

Ehlers (1990, 1994) and Stephan (1995) suggested that during the Elsterian glaciation two ice sheets crossed Schleswig-Holstein. The first one advanced from the north and the second one from the NE. The Elsterian glaciation of north-western Germany was associated with the formation of glacial channels (“tunnel valleys”) which were eroded by highly pressurized subglacial melt water and

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were subsequently filled with glacial deposits (Piotrowski, 1991; Piotrowski and Tulaczyk, 1999). The southern boundary of the Elsterian glaciation is not known in much detail. Most reliable data for the reconstruction of ice sheet thickness and the position of former Elsterian ice margins come from Saxony and Thuringia (Wagenbreth, 1978; Eissmann, 1995; Unger and Kahlke, 1995; Eissmann, 1997; Junge, 1998), whereas to the west the extent of the Elsterian ice sheet is poorly defined, being obscured by an overprint of the Saalian glaciation (Ehlers et al., 1984; Kaltwang, 1992; Klostermann, 1992, 1995; Caspers et al., 1995). However, all data indicate a complete ice coverage of the Schleswig-Holstein area (Ehlers, 1990, 1994; Stephan, 1995; Ehlers and Gibbard, 2003; Ehlers and Gibbard, 2004).

During the Holsteinian interglacial, marine clays were deposited in Schleswig-Holsteins Tunnel Valleys. The beginning of the Saalian is characterized by a period of cold climate but without ice coverage (Ehlers, 1994). Three subsequent major ice advances are known for the Saalian glaciation in northern Germany. Tills are separated by glaciolacustrine and glaciofluvial deposits, but no interglacial sediments have been found (Skupin et al., 1993; Ehlers, 1994; Caspers et al., 1995; Stephan, 1995).

Ehlers (1990) suggested that the northern part of Schleswig-Holstein was permanently covered by ice during the last two Saalian stages. Data from the North Sea offshore Schleswig-Holstein indicate an ice free, periglacial area towards the west (Schwarz, 1996). During the Eemian interglacial the area of the North Sea was affected by a transgression and marine sediments were deposited. In topographically higher areas of Schleswig-Holstein limnic sediments were deposited in morphological depressions (Stephan, 1995).

Most authors assume that the first advances of the Weichselian ice sheet did not occur before 25 kyr BP (Stephan and Menke, 1993; Ehlers, 1994). Therefore, during most of the Weichselian time Schleswig-Holstein was not covered by ice. The dynamics of advancing and retreating ice sheets in northern Europe during the Weichselian is summarized by Boulton et al. (2001). From 25 to about 13 kyr BP at least 3 ice advances from the northeast are known from Schleswig-Holstein, whose deposits make up most of recent landforms (Stephan, 1995).

1.2. Mittelplate petroleum system

The area of Schleswig-Holstein, as part of the Central European Basin System (CEBS), is an intensely explored and developed hydrocarbon province. Extensive basin modelling was carried out in this basin (e.g. Bueker et al., 1995; Neunzert et al., 1995, 1997; Erdmann, 1999; Hertle et al., 1999; Petmecky et al., 1999).

Dominating structural features are Permian (Rotliegend and Zechstein) and Triassic salt diapirs, mostly striking NNE to SSW. Halokinetic movements started during the Triassic and resulted in the formation of thick sedimentary sequences within rim synclines between the salt diapirs. The most important rim synclines on the Holstein Block are the Westholstein and the Ostholstein Troughs. The importance of these Jurassic Troughs for the petroleum geology of Schleswig-Holstein is linked to the occurrence of thick layers of the prominent Liassic Posidonia Shale source rock (Welte, 1979; Wehner et al., 1989). The Posidonia Shale also charged the reservoirs at the Mittelplate oil field (Müller et al., 2004). The overlying deltaic Middle Jurassic Sandstones serve as prolific reservoir rocks (Berners et al., 1992). The two Jurassic Troughs contain the major petroleum system known so far in Schleswig-Holstein.

The Mittelplate field is the biggest oil accumulation in Germany at present and annual production is in the order of about 2.2 Mio tons of crude oil (Pasternak et al., 2006). The field is located in the tidal flat area at the south-western nearshore of Schleswig-Holstein (Fig. 1). Because of its economic significance, petroleum geology of the Mittelplate area is well known (Berners et al., 1992; Junker and Dose, 2001; Langhans et al., 2003; Müller et al., 2004).

The dynamics of petroleum generation, migration and entrapment were most recently investigated by an integrated petroleum systems modelling approach using the PetroMod (IES, Aachen, Germany) software (Grassmann et al., 2005). By integrating all available geological data, the burial history and the temporal development of the temperature field were reconstructed. 2D basin modelling included the organic geochemical analysis of maturity indicators, the reconstruction of sedimentation and the calibration of the thermal history as well as the modelling of petroleum generation and migration. The complex history of salt diapirism is the key in understanding the development of the Mittelplate field. Maturation and petroleum generation within the Posidonia Shale were governed by temporal and spatial changes in temperature caused by extensive salt tectonics within a complex structural framework.

1.3. Influence of cyclic glaciations on petroleum systems

The most obvious impacts of ice sheets on sedimentary basins are changes in the structural and depositional settings. During ice advance glaciers may erode sediments at their base, during melting of an ice sheet glacial sediments can be deposited. In addition, the overburden of the ice leads to isostatic subsidence of the basin while unburden after ice retreat results in isostatic uplift. The spatial and temporal variations of these processes during advancing and retreating ice sheets can lead to changes in the pathways and the intensity of hydrocarbon migration and can even cause spilling of existing petroleum accumulations. For example,

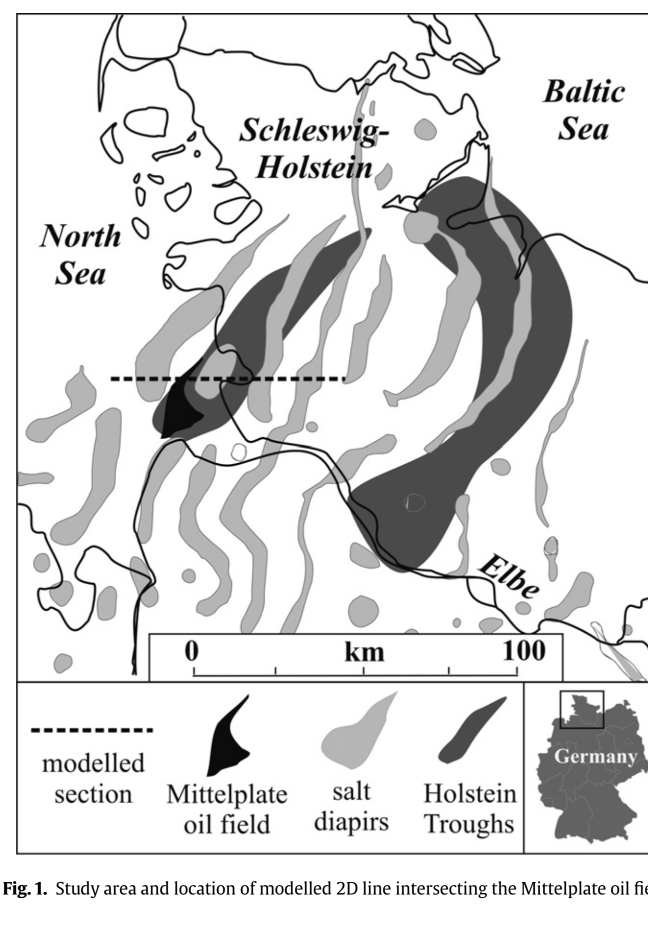

Fig. 1. Study area and location of modelled 2D line intersecting the Mittelplate oil field.