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Improving spatial predictability of petroleum resources within the Central Tertiary Basin, Spitsbergen: A geochemical and petrographic study of coals from the eastern and western coalfields

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ABSTRACT

Central Tertiary Basin (CTB) coals from a variety of palaeogeographic conditions within the Longyear and Verkhnij seams, were sampled to assess the relationship between the petroleum present, the remaining generation potential and coal geochemistry in order to improve the spatial predictability of petroleum resources within the basin. Vitrinite reflectance (VR) values from the CTB coals have been shown to be suppressed (Marshall et al., 2015b). This study attempts to quantify and correct for this suppression effect by applying the Lo (1993) method (LoVR), which uses Hydrogen Index (HI) values to modify VR data, and the coal Rank(S_r) scale of Suggate (2000, 2002), a technique not affected by suppression. In addition, the oil generation and expulsion thresholds for the CTB coals were investigated, with discussions on oil potential versus marine influence upon the mires in which the coals formed.

A pseudo-van Krevelen diagram shows that the majority of the coals plot on the Type II kerogen line, while the remainder plot between the Types II and III kerogen lines, with HI between 151 and 410 mg HC/g TOC; however, maceral analysis shows that Type III kerogen predominates. This is attributed to the presence of abundant fluorescing (oil-prone) vitrinites. The LoVR, T_{max} and Rank(S_r) parameters all show that maturity increases from basin margins towards basin centre (i.e. from Bassen to Lunckefjellet, to Breinosa and Colesdalen) and indicate that all the coals are within the oil generation window. The marginal samples at Bassen are within the early mature stage of the oil window (i.e. ~0.7% R_O); meaning the threshold for oil generation in the basin could not be clearly defined. However, the observed maturation trend somewhat parallels the maturation pathway of the New Zealand Coal Band (NZ Coal Band) and the “envelope” of the Sykes and Snowdon (2002) NZ coal data-set; therefore, it is considered that the oil generation threshold for the CTB coals is likely at Rank(S_r) ~9–10, T_{max} ~ 420–430 °C in line with the observed rise in Bitumen Index (BI). Some of the Lunckefjellet coals and all the Breinosa and Colesdalen coals have either reached or progressed beyond the threshold for oil expulsion as indicated by the peak in HI at Rank(S_r) ~11–12, LoVR ~0.75–0.85% R_O, T_{max} ~ 430–440 °C. The peak in BI at Rank(S_r) ~12.5–13.5 suggests that some of the Lunckefjellet and Breinosa coals, and all the Colesdalen coals have reached the “effective oil window”.

Total sulphur (S_T) contents range between 0.46 and 12.05% indicating non-marine to strong marine influence upon precursor peats, with S_T contents of the Longyear seam appearing to record instances of coastal retreat associated with base level rise. Marine deposition seems to significantly control the distribution of oil-prone coals within seams and across the CTB. The levels of marine influence (as indicated by S_T content) show clear positive relationships between BI and HI within the Bassen samples because they have not started expelling oil. Conversely, the levels of marine influence show clear negative relationships with BI and HI within the Colesdalen samples because they have commenced oil expulsion, and probably reached the “effective oil window”. The

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more marine influenced coals appear to have commenced petroleum generation relatively earlier, which is a plausible explanation why the coals from the Lunckefjellet locality appear to be at different stages within the oil window.

1. Introduction

The Central Tertiary Basin (CTB) Spitsbergen, Svalbard, contains large reserves of perhydrous (oil-prone) coals, with oil potential attributed to perhydrous vitrinites formed as a consequence of peat deposition under marine influence (Orheim et al., 2007; Marshall et al., 2015a, b). The greatest oil potential in these coals has been hypothesised to be favoured by environmental conditions within the precursor peat including: relatively high marine influence upon the peatlands which resulted in increased sulphur content (≥ 0.5%), high bacterial degradation (> 100 μg/g TOC hopanes), stable hydrology and fen (rheotrophic) depositional conditions (Marshall et al. 2015a). However, this interpretation is based on samples from only 3 localities in the eastern coalfield, and thus covers only a limited range of palaeogeographic settings, an important factor on the level of marine influence upon the mires in which the CTB peats/coals formed (Marshall et al., 2015a). One of the aims of this study is to re-evaluate the interpretations of Marshall et al. (2015a) using a wider range of samples from multiple seams across 7 localities including the eastern and western coalfields. By doing this, we will re-assess the main control(s) on the petroleum potential of the coals taking into account a wider range of parameters, and so provide a practical guide that could be used in identifying areas of greatest remaining oil potential in the basin.

Source rock maturity can be determined using either vitrinite reflectance (VR), T_{max}, biomarkers etc., although for coals, VR is the most widely used. Reason being that it is the only single parameter that can be measured in coal over a wide range of thermal maturities; i.e. from early maturity (lignite) to post-maturity (low volatile bituminous), and shows relative uniform physio-chemical changes which result in an almost linear increase with increasing thermal stress (Teichmüller and Teichmüller, 1979; Mukhopadhyay, 1994). However, there is a specific problem with perhydrous vitrinites in that they frequently show lower reflectance than the orthohydrous vitrinites, and are often referred to as having suppressed reflectance. The presence, recognition and properties of suppressed VR have been widely discussed (Hutton and Cook, 1980; Taylor and Liu, 1987; Teichmüller, 1989; Raymond and Murchison, 1991; Taylor, 1991; Hao and Chen, 1992; Wilkins et al., 1992; Powell and Boreham, 1994; Petersen and Rosenberg, 1998; Petersen and Vosgerau, 1999; Carr, 2000; Petersen et al., 2009). Marshall et al. (2015b) investigated the unusual VR variations within the CTB coals and concluded that the VR values are suppressed; these workers observed a general decrease in VR towards the top of the Longyear seam, and roughly estimated the true, non-suppressed VR by adopting the measured VR of the least suppressed sample (from the lower parts of the seam) per location sampled. This paper will use two different approaches towards estimating the true maturities of the CTB coals; namely: 1) the Lo (1993) method, which incorporates the HI and measured VR data, and 2) the coal Rank(S_r) scale of Suggate (2000, 2002) which utilises cross plots of calorific value (CV) and volatile matter (VM).

Despite VR being suppressed towards the seam roof, a coal seam can be considered to be isometamorphic. Meaning that the least suppressed values from the lower parts of the seam as reported by Marshall et al. (2015b) are correctly considered as indicators of thermal maturity; however, this study will examine this in detail. Also, the relationship between the data from various maturity parameters will be examined and discussed. If the LoVR values show consistency with other maturity parameters, then the Lo (1993) method may be applied to correct for VR suppression in the absence of the more accurate Suggate (2000, 2002) Rank(S_r) scale or FAMM (fluorescence alteration of multiple macerals) measurement from which the unsuppressed VR can be estimated (Wilkins et al., 1992, 1998; Petersen et al., 2009). In addition to the suppression of VR, T_{max} can also be suppressed in perhydrous coals and source rocks. In a study of New Zealand Eocene coals, Newman et al. (1997) observed that T_{max} was lower in perhydrous coals than in the other coals (orthohydrous) with the same burial and thermal histories. Similarly, the T_{max} values of Canadian Cretaceous high HI coals have been noted to be anomalously low (Snowdon, 1995). Sykes and Snowdon (2002) also observed T_{max} suppression in Late Cretaceous – Cenozoic coals from New Zealand. Therefore, this study will also assess T_{max} suppression within the CTB coals.

Furthermore, this study aims to examine and discuss the thresholds for oil generation and expulsion in the CTB with reference to the maturation pathway(s) defined by published coal data-sets from around the world.

2. Geological setting

The Svalbard archipelago, located between latitude 74° and 81° north, and between longitude 10° and 35° east, is the exposed part of the Barents Sea platform; it is situated on the NW corner of the Eurasian continental plate, with rocks ranging from the Archean to Quaternary in age (Harland et al., 1997). The opening of the North Atlantic Ocean caused dextral movement between Svalbard and eastern Greenland, with oblique compression (transpression) leading to the development of the West Spitsbergen Fold and Thrust Belt (Eldholm et al., 1987; Bergh et al., 1997; Leever et al., 2011). The transpressional event was probably short lived, being linked to a shift in the spreading direction of the Labrador Sea prior to the earliest Eocene seafloor spreading (Gaina et al., 2009), and there is a suggestion that compression peaked in Early Eocene (Tegner et al., 2011). The CTB and the linked West Spitsbergen Fold and Thrust Belt form a 100–200 km wide NNW-SSE striking zone in western and central Spitsbergen, with the wedge-top CTB located in a broad NNW-SSE trending syncline. This structure has a steeper limb to the west and a gently rising limb towards the east (Bergh et al., 1997; Braathen et al., 2012). The basin formed firstly as a broad platform linked to North-East Greenland (Piepjohn et al., 2013) and gradually evolved to a foreland basin, which developed in response to the West Spitsbergen Fold and Thrust Belt (Bruhn and Steel, 2003). The Paleocene - Eocene CTB fill overlies Lower Cretaceous strata and contains the majority of the economic coal bearing units, which belong to the earliest phase of the basin fill deposited in a paralic setting (e.g. Nagy, 2005) within a humid temperate climate (Marshall et al., 2015a). In the CTB, mining is concentrated within the Todalen Mb. of the Firkanten Fm. (Orheim et al., 2007), which is generally dated as early Paleocene (e.g. Livshits, 1974; Harland et al., 1997; Nagy, 2005). Five main coal seams are commonly cited within the Todalen Mb. which are: Svea, Todalen, Longyear, Svarteper and Askeladden seams (Fig. 1). However, in the western parts of the CTB, only three coal seams are present (Nidzny, Verkhnij and Sputnik seams e.g. Marshall, 2013) and there is no report on their oil potential. This study focuses on the Longyear and Verkhnij coals.

3. Samples and methods

3.1. Samples

47 coal samples from the Longyear seam in Bassen, Lunckefjellet and Breinosa (eastern coalfield of the CTB), and the Verkhnij seam in Colesdalen (western coalfield of the CTB) have been used for this study