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Redox conditions, productivity, and volcanic input during deposition of uppermost Jurassic and Lower Cretaceous organic-rich siltstones in Spitsbergen, Norway

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In this paper, uppermost Jurassic and Lower Cretaceous black organic-rich siltstones (Rurikfjellet Formation) from Carolinedalen (Isfjorden, Spitsbergen) are studied using integrated palynological, petrographic, and geochemical methods (organic and inorganic geochemistry as well as Rock-Eval pyrolysis) in order to decipher the depositional conditions prevailing during their sedimentation, the type of organic matter from which they were formed, and their potential for generating hydrocarbons. The age of these investigated sediments encompasses an interval from the upper Tithonian-Berriasian to the Hauterivian, dated on the basis of dinocyst biostratigraphy. The ammonoids found in loose form at the base of the investigated section, such as *Laugeites groenlandicus*, are indicative of the upper part of the middle Tithonian. Based on palynology, biomarkers, and Rock-Eval data, the kerogen in the investigated siltstones from Isfjorden is of the mixed II/III type; the organic matter is mixed marine and terrestrial in origin, and represents the early to peak 'oil window' maturation stage (T_{max} around 440 °C).

These siltstones were deposited under a high-productivity regime with oxic/dysoxic bottom water conditions, as evidenced from the size distribution of pyrite framboids, in which pyrites with diameters >5 μm predominate. Values of Th/U and C_{org}/P ratios generally above 3 and 30, respectively, along with pristane/phytane ratios >2 and sterane/hopane ratios <0.3, also indicate oxic to suboxic sedimentary conditions in the water column. Anoxia, if present, must have been short-lasting and formed oxygen minimum zone in the water column. Elevated productivity in the photic zone may have been generated by an increase in volcanic activity, as confirmed by higher Hg contents and/or terrigenous nutrient supply.

1. Introduction

The Early Cretaceous was a time of very important global changes in marine environments related to the opening of numerous rift basins during the break-up of the Pangaea supercontinent and to a high level of volcanic activity on land and in the sea (Föllmi, 2012). This period is generally characterised by a greenhouse climate, high atmospheric concentrations of CO_2, high global mean temperatures, and high sea level (see e.g. Littler et al., 2011; Föllmi, 2012), but some cooling episodes were also recognized (e.g. Price, 1999). These conditions favoured the formation of organic-rich rocks, often characterised by supra-regional occurrence, which originated during oceanic anoxic events (OAEs) and/or episodes of environmental changes (see Föllmi, 2012). According to Föllmi (2012), Early Cretaceous episodes of environmental changes are defined by their characteristic carbon-isotope signature and/or occurrence of organic-rich deposits. The main causes of OAEs and episodes of environmental changes are still being debated. One of the problems is identifying the main factor causing high organic carbon accumulation rates: high productivity in the photic zone of the water column, enhanced preservation in oxygen-depleted deep waters, or a combination of both processes (Nederbragt et al., 2001

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and references therein). The Lower Cretaceous organic-rich rocks in other regions are often regarded as source rocks for hydrocarbons (e.g. Plummer, 1994; Mutterlose et al., 2003; Creaney and Sullivan, 2011; Yang et al., 2014; Makeen et al., 2015; Zuo et al., 2017).

The Jurassic-Cretaceous transition at Spitsbergen is characterised by the occurrence of a thick succession of organic-rich clays, shales, and siltstones, which are considered source rocks for hydrocarbons, while the sand-rich intercalation may represent reservoirs (e.g. Harland and Kelly, 1997). These sediments belong to the Janusfjellet Subgroup, divided by Parker (1967) into the older Agardhfjellet Formation (Bathonian to Tithonian) and younger Rurikfjellet Formation (Berriasian to upper Hauterivian or even Barremian; cf. Dypvik et al., 1991b; Grøsfjeld, 1991; Harland and Kelly, 1997). The latter is overlain by the continental Helvetiafjellet Formation, characterised by sand-rich sediments with footprints of dinosaurs (e.g. de Lapparent, 1962; Birkenmajer et al., 1982; Grøsfjeld, 1991; Dypvik et al., 1991a,b; Harland and Kelly, 1997; Gjelberg and Steel, 2012). Organic-rich sediments of the Agardhfjellet Formation were partly deposited under oxygen-depleted conditions (Dypvik, 1985; Dypvik et al., 1991a; Nagy et al., 2009).

The aim of the present study is to decipher depositional conditions prevailing during the sedimentation of organic-rich rocks of the Rurikfjellet Formation (?upper lower Tithonian–Berriasian to Hauterivian) outcropped at Carolinedalen (Isfjorden) in central Spitsbergen, and the potential of these rocks for the generation of hydrocarbons, based on integrative palynological, inorganic and organic geochemical, and petrographic methods.

2. Geological setting

The deposits of the Janusfjellet Subgroup are dominated by dark grey clays with significant contributions of silt and sandstone sediments which originated in a clastic shelf environment (e.g. Parker, 1967; Dypvik et al., 1991a, b, 1992; Harland and Kelly, 1997). This Jurassic-Cretaceous succession was extensively investigated by e.g. Frebold (1928, 1929), Sokolov and Bodylevsky (1931), Frebold and Stoll (1937), Różycki (1959), Parker (1967), Løfaldli and Thusu (1977), Bjærke et al. (1976), Birkenmajer et al. (1982), Dypvik (1978, 1985, 1992), Bäckström and Nagy (1985), Doyle and Kelly (1988), Dypvik et al. (1991a, b, 1992, 2002), Dypvik and Harris (2001), Hammer et al. (2011), and Nakrem and Kiessling (2012).

The deposits of the investigated Rurikfjellet Formation range from 40 to 290 m in thickness (Harland and Kelly, 1997) and represent deep-shelf to deltaic system palaeoenvironments. This Formation was subdivided into the Myklegardfjellet Bed and the Wimanfjellet and Ullaberget members (Dypvik et al., 1991a, b; Harland and Kelly, 1997). The Myklegardfjellet Bed, situated at the base of the Wimanfjellet Member, is developed as a distinct clay horizon, 0.5–2 m thick, often characterised by grey or yellow colouration (Birkenmajer, 1980; Dypvik et al., 1991a). The Wimanfjellet Member is developed as dark grey and partly silty shales, with some bioturbation and lenticular sideritic concretions (Dypvik et al., 1991a, b; Harland and Kelly, 1997). In central Spitsbergen, the thickness of this member varies between 60 and 120 m and decreases eastwards (Dypvik et al., 1991a). The Ullaberget Member is developed as fine-grained sands with silts and shales and contains hummocky cross-stratification, planar bedding, and bioturbation, as well as several coarsening-upwards sequences. This succession may reflect prodeltaic palaeoenvironments (Dypvik et al., 1991a).

The age and lithology of the investigated succession are indicative of the Wimanfjellet Member. The investigated sections are located in the cliffs exposed at Carolinedalen (78°19′36.2″ N, 15°42′34.2″ E), on the southern bank of Isfjorden, approximately 10 km north of Longyearbyen (Fig. 1). The studied samples come from uppermost Jurassic and Lower Cretaceous organic-rich black or dark grey siltstones over 40 m thick (Rurikfjellet Formation, Wimanfjellet Member; Fig. 2). Two sections were sampled: 1) at the lower part of the cliff, here referred to as the CA section, and 2) exposed in the upper part of cliff, here referred to as the CD section (Fig. 3). The investigated black siltstone deposits, especially those in the lower part (CA) of the section, contain numerous fossils such as ammonoids, bivalves (e.g. *Buchia*, ?*Corbicella*, *Lima* (*Pseudolimea*), *Oxytoma*), and scaphopods. The fossil content is significantly reduced in the CD section.

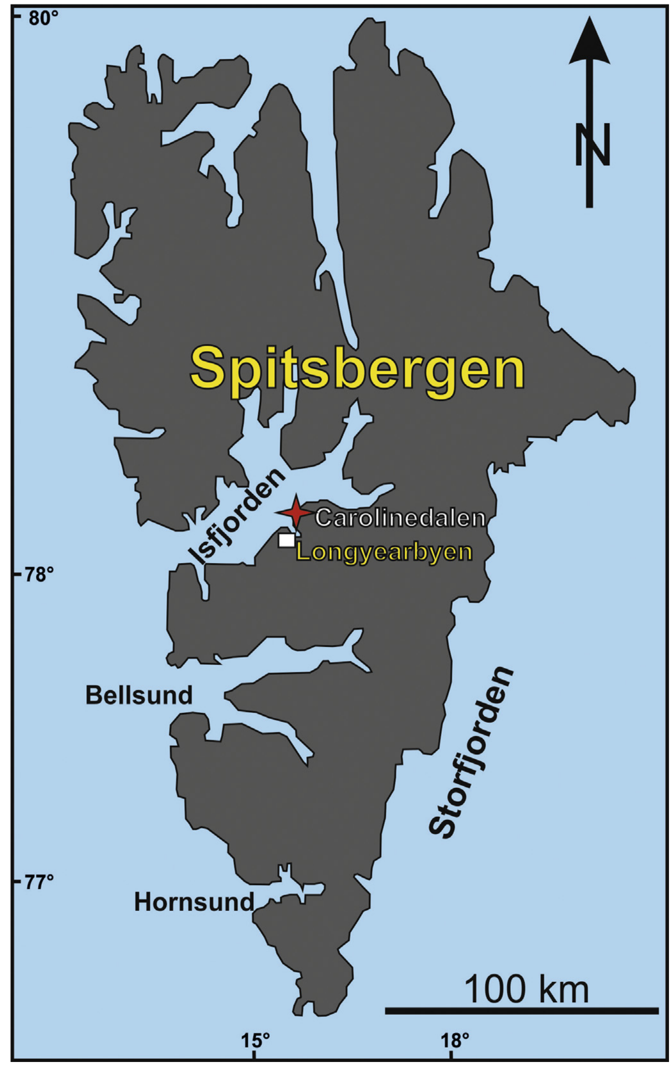

Fig. 1. Map of Spitsbergen showing the location of the investigated sections at Carolinedalen.

3. Material and methods

The fieldwork was carried out in August 2013. In the lower CA section, consisting of dark grey or black siltstones 26 m thick with sideritic horizons, 62 samples were collected. In the upper CD section, comprising dark grey siltstones 19.3 m thick with numerous sideritic concretion horizons and nodules, 23 samples were collected. These 85 samples in total (Figs. 10, 11; see also Supplementary Materials SM1, 2) were then analysed using various methods in order to decipher the details of palaeoenvironmental