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Petrological and geochemical characteristics of Palaeogene low-rank coal on the Faroe Islands: Restricted effects of alteration by basaltic lava flows

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ABSTRACT

The first combined petrographic and geochemical investigation of coal from the Faroe Islands was performed as a case study to understand thermal effects from basaltic lava flows on immature coal. The samples were divided into two distinct groups: "normal" coal (xylite and detroxylite) and "altered organic matter" (charcoal and organic particles dispersed in samples rich in altered clastic mineral components or enriched via hydrothermal fluids). The "normal" coal consists primarily of huminite-group material dominated by ulminite. The proportions of material from inertinite and liptinite groups vary from sample to sample. The studied macerals are anisotropic with no observed reaction rims or vacuoles. According to the mean ulminite reflectance in combination with ultimate and proximate analyses, the coal reached the lignite and subbituminous stages. The maceral compositions together with coal palynology indicate a predominance of gelified wood-derived tissues and demonstrate that the coal evolved in wet forest swamps under limno-telmatic to telmatic conditions.

Alteration effects on immature coals from overlying basalt flows were relatively limited. Due to relatively rapid heat loss from the basaltic lava, as verified by the presence of volcanic glass (tachylyte), its imposed thermal effects resulted only in development of a thin "anthracite-like" crust on samples with no elevated coal rank. Associated hydrothermal fluids induced coal hydrofracturing with subsequent mineral precipitation and decomposition of the ambient feldspar-rich volcaniclastic sediments. Altered organic matter is enriched in SiO_2, Al_2O_3 and FeO_{tot}, as well as in trace elements such as Ni and Cr. In contrast, these samples are depleted in Hg (<10 ppb).

1. Introduction

The Faroe Islands (1400 km^2; 4° S of the Arctic Circle) belong geologically to the North Atlantic Igneous Province (Saunders et al., 1997). Massive basalt lava flows of Palaeocene age (Storey et al., 2007) are interbedded with sedimentary layers containing thin coal lenses and seams. Continental interlava volcaniclastic sediments on the Faroe Islands provide only limited palaeontological evidence (plant remains, rare trace fossils) and their depositional environment has been highly debated (Pokorný et al., 2015 and references therein).

Coal has been a key fuel for the Faroe Islands, particularly in the past, due to their isolated geographical position and the limited import of fossil fuels. Because of its importance the coal was locally named "black gold" and has been mined in many adits since the 18th century to ensure energy self-sufficiency. Coal productivity in 1930 was approximately 5000 tons/year. Since the beginning of the 21st century, production has decreased to 100 tons/year (Øster-Mortensen, 2002). For this reason, only one coal mine has been in operation since 2008.

The coal deposits are mentioned peripherally in several publications within basic geological descriptions of the Faroe Islands (e.g., Ellis et al., 2002; Laier et al., 1997; Lund, 1989; Parra et al., 1987; Passey, 2014; Rasmussen and Noe-Nygaard, 1969, 1970; Stokes, 1874). Nevertheless, they have not yet been systematically studied in terms of quality.

The chemical composition of coal varies considerably on the global scale (Mukherjee et al., 2008). The differences involve major element compositions (e.g., the commonly observed sulphur content) and trace element contents. The increasing environmental burden associated with the burning of fossil fuels places demands on the regulation of pollutants emitted into the atmosphere. Coal combustion leads to the vaporization of metals, which subsequently condense as an aerosol of submicron-sized particles. The emission of metals into the atmosphere depends on the vapour pressure of each element (Finkelman et al.,

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1990). Trace elements in coals are subdivided into five categories according to the degree of possible health risk (Zhang et al., 2004). The most hazardous metals are: As, Cd, Cr and especially Hg (Swaine and Goodarzi, 1995). The negative influence of non-metals such as fluorine emitted during indoor combustion of a F-rich coal containing a binder clay has also been observed (Dai et al., 2007).

Mercury begins to be released from coal at temperatures below 200 °C; above 600 °C it occurs in the form of Hg^0 (Mukherjee et al., 2008). For this reason, mercury released into the atmosphere during coal combustion (Yudovich and Ketris, 2005a, 2005b) is a significant pollutant, despite its generally low concentrations in coal (Ketris and Yudovich, 2009; Xu et al., 2013). However, extremely-high Hg concentrations (up to 12.1 ppm) were reported from some Chinese coals and coal ashes (Dai et al., 2006, 2012a, 2014). Long-range mercury transport, enabled by cycles of deposition and reemission, considerably increases mercury concentrations in subpolar and polar regions (Poissant et al., 2008). This effect is also apparent from the increased levels of mercury in Faroese peat. Maximum concentrations of 498 ppb total Hg were determined in peat from 1954, at the peak of coal production (Shotyk et al., 2005).

The composition of coal can be affected by volcanic activity. Several authors have studied various properties of thermally altered coal from all over the world (Bussio and Roberts, 2016; Dai and Ren, 2007; Golab and Carr, 2004; Merritt, 1985; Rahman and Rimmer, 2014; Singh et al., 2007, 2008; Wang et al., 2014; Ward et al., 1989; Yao and Liu, 2012). Ward et al. (1989) categorized the layers around an igneous body into four zones: i) zone of porous cinder close to the contact; ii) zone of visibly banded cinder with remnants of the original lithotype stratification; iii) zone of heat-affected coal without porosity and other microscopic and macroscopic signs of coking; iv) zone of unaffected coal. Kwiecińska and Petersen (2004) defined cinder from the contact zone as natural char and coke. Physical and chemical effects of intrusions on peat and coal depend on exposure to heat, time of igneous emplacement, temperature, thickness and form of the igneous body, pressure, hydrology, as well as the composition and initial coal rank of the affected formation, lithology of the surrounding rocks and other local factors (Bostick and Pawlewicz, 1984; Crelling and Dutcher, 1968; Suchý et al., 2002). In heat-affected coal, microconstituents formed by the alteration of vitrinite and liptinite macerals, having different textural and optical properties than the original macerals, are commonly recognized (Taylor et al., 1998). Typical optical changes in coal caused by intrusion/effusion involve microbrecciation, increases in vitrinite reflectance, development of devolatilization pores and fissures, coke textures and the presence of pyrolytic carbon. Pores of natural coke are empty or filled with mineral or carbonaceous matter formed from volatile material (Amijaya and Littke, 2006; Goodarzi and Cameron, 1990; Khorasani et al., 1990; Kisch and Taylor, 1966; Mastalerz et al., 2009; Suchý et al., 2002). The product formed from vitrinite and liptinite of the bituminous coal at temperatures above 500 °C is an anisotropic coke with a mosaic structure and higher reflectance than the original vitrinite (Kwiecińska and Petersen, 2004).

The goal of this pilot study is threefold: i) to describe the petrography and geochemistry as well as the coal rank of Palaeogene coal from the Faroe Islands; ii) to assess its depositional environment; iii) to characterize the effect of basaltic effusions overlying coal-bearing strata on the coal composition.

2. Geological setting

The Faroe Islands were formed during extensive volcanic activity within the North Atlantic Igneous Province in response to the opening of the Atlantic Ocean (Jolley and Bell, 2002). This part of the North Atlantic Igneous Province is named the Faroe Islands Basalt Group and extends to the east and southeast from the current Faroe Islands to the Faroe-Shetland Basin. Volcanic rocks of the Faroe Islands Basalt Group are petrographically classified as aphyric basalts with a fine-grained groundmass, plagioclase-phyric basalts and olivine-phyric basalts (Noe-Nygaard and Rasmussen, 1968).

Rasmussen and Noe-Nygaard (1969, 1970) described three tholeiitic basalt series (~6.6 km thick): lower, middle and upper basaltic lava formations that are thought to overlie older continental crust (Bohnhoff and Makris, 2004, Bott et al., 1974; Casten, 1973; Richardson et al., 1998).

The oldest basalt flow yielded an $^{40}Ar/^{39}Ar$ plateau age of 63.1 ± 1.8 Ma (Waagstein et al., 2002). After termination of the initial volcanic phase, sediment deposition began. Subsequent volcanic activity produced the middle basaltic lavas and when this ceased, a coal-bearing sedimentary sequence was formed during the period between 58 and 56 Ma (Jolley and Bell, 2002; Storey et al., 2007). Finally, the coal-bearing sedimentary sequence was covered by the upper basalt flows.

According to Passey and Jolley (2009), tholeiitic lavas of the Faroe Islands can be further subdivided into seven lithostratigraphic formations (Figs. 1, 2). The basal Lopra Formation (1.1 km thick) is known only from the onshore Lopra-1/1A borehole and consists of basalts, volcaniclastic sandstones and hyaloclastites. The subsequent 3.25-km-thick Beinisvørð Formation is made up of basaltic lavas, volcaniclastics and sandy claystone to mudstone sediments that may contain thin coal lenses. The Beinisvørð Formation is overlain by up to 15 m thick coal-bearing Prestfjall Formation, deposited between eruptions, which consists predominantly of tuffitic claystones and volcaniclastic conglomerates. The Prestfjall formation is overlain by the syn-eruption Hvannhagi Formation of pyroclastic sediments, up to 50 m thick. This formation is covered by basaltic lava flows with a total thickness of 1.4 km named the Malinstindur Formation and the 30-m-thick sedimentary Sneis Formation dominated by sandstones and conglomerates. The volcanic activity terminated with basaltic lava flows forming the 900-m-thick Enni Formation that is interbedded with volcaniclastic sequences. The landscape of the Faroe Islands was subsequently reshaped by Pleistocene glacial activity.

3. Samples and methods

To examine the petrological and geochemical composition of Faroese coal, a total of 22 bench samples with well-known positions within the coal-bearing sequence were taken from the Prestfjall Formation on Suðuroy Island and one from the Beinisvørð Formation on Mykines Island (Fig. 1, Table 1). Sampling was performed both in coal mines and coal-bearing sedimentary profiles (Fig. 3A–F), following ISO 5069-1:1983 standard procedure. The sampled localities were described in detail by Kuboušková et al. (2015). Coal samples were air-dried and stored in polyethylene bags for transport.

Additionally, on Suðuroy Island it was possible to collect basalt samples (Malinstindur Formation; 5 samples) directly overlying the Prestfjall Formation that contains the studied coal occurrences (Fig. 3D, E) and two samples of tuffitic coal-bearing claystone changed to porcelanite along the contact of these formations. Thin sections made from these samples were investigated using an Olympus BX50 petrographic microscope.

3.1. Petrographic analyses

The coal samples were the subject of petrographic investigation, i.e., maceral analysis of huminite, liptinite, inertinite groups and mineral group divided into clay minerals, sulphides, carbonates and other particularly accessorial minerals and altered minerals, and measurement of the reflectance of ulminite and altered organic matter (ISO 7404-3: 2009, Taylor et al., 1998).

For petrographic analyses, polished sections were prepared and studied both in reflected and ultraviolet light using an Olympus BX51 microscope with Zeiss Photomultiplier MK3 system and fluorescence mode using immersion lens with 40× magnification. The Pelcon point counter was used for the maceral analysis. Coal rank was determined by reflectance measurements on ulminite B from particulate polished sections by SpectraVision software calibrated with yttrium aluminium garnet (R = 0.894%), sapphire (R = 0.596%), spinel (R = 0.422%) and