**Oligo-Miocene subbituminous coal in a microtidal environment reworked during
Quaternary periglacial conditions (Western Falkland Islands/ Isla Gran Malvina)
– Coal formation and natural sand processing**

Dill H.G. ^{*1}, Kus J.^{**}, Kaufhold, S.^{**}, Rammlmair, D.^{**}, Techmer A. ^{***}

*Gottfried Wilhelm Leibniz University, Welfengarten 1

D-30167 Hannover, Germany

** Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover,
Germany

*** Leibniz Institute of Applied Geosciences

P.O Box 510163, D-30631 Hannover, Germany

Abstract

The Western Falkland Islands are characterized by landforms and sediments of Quaternary age originating from the interplay of periglacial and marine processes. These have left their imprints on siliciclastic sediments and subbituminous coal, peatland, and podzolic soil. The white quartz sand and a subbituminous coal seam are in the focus of investigations (coal petrography, carbon isotope analysis, sedimentary petrography, clay mineralogy, granulometric, morphometric studies), and geochemistry. The study of the coal-sand couple may shed some light on two different parts of geology. Firstly, it broadens the knowledge of the regional geology at the southern tip of South America, how coal seams may be emplaced in a periglacial-microtidal environment. Secondly, the study is also relevant for applied geology, how sand is processed in a coal-bearing paralic regime. The coal-sand couple evolved during 6 discrete stages. Stage I: The detrital parent material has been derived from the Siluro-Carboniferous Gran Malvina Group. Stage II: From the Oligocene through the late

¹ Corresponding author: Harald G. Dill (retired): E-mail: haralddill@web.de, website: hgeodill.de

Miocene under a warm tropical climate organic matter was accumulated in a paralic environment giving rise to subbituminous coal. Stage III: During the Pleistocene alternating erosion and deposition in a wave-dominated coastal-marine regime gave rise to the built-up of the coal layer (allochthonous) interbedded into sand. The hydrodynamic regime reduced the grain size to the level of medium to fine sand, it enhanced its sorting coefficient and caused the separation of minerals according to their specific gravity (mechanical processing). Stage IV: The subbituminous coal seam has been reworked by the last glacial progradation. Stage V: Wind and water were accountable for the morphology of grains to gradually approaching the sphere and the content of heavy minerals to increase along the backshore and in the dune belt. Stage VI: Organic acids derived from the coal promoted the chemical leaching. It significantly contributed to the decrease of the labile constituents of arenites (feldspar, carbonates minerals, and calcareous tests of faunal remains). Chemical alteration was grinded to a halt by another sea level rise, which gradually destroyed the coal layer. The depositional environment most effective for the processing of sand is located in the microtidal setting. In the meso- to macrotidal hydrodynamic regime the chemical leaching becomes the only efficacious tool to improve the quality of the footwall rocks. Due to the predominance of argillaceous sediments there, the quality of clay is enhanced and, e.g., kaolin deposits may come into existence.

Keywords: *Subbituminous coal; paralic; periglacial; high-purity quartz sand; Falkland Archipelago*

1. Introduction

Considering the economic geology of the Quaternary, two commodities stand out by their widespread occurrence: Peat and sand.

Peatlands cover vast areas laid bare after the retreat of the ice shields (Yu et al., 2003; De Jong et al., 2006; Yeloff et al., 2007; Mauquoy et al. 2008; Booth et al., 2010). The majority of studies published on these peatlands deal with climate change in these sediments. The final use of peat as fossil fuel and for melioration in horticultures is often eclipsed by such investigations (Paappanen et al., 2006; Dill et al., 2008a). The predecessor of the Holocene age, the Pleistocene arenaceous series were, in places, described to host subeconomic subbituminous coal-like beds (Stephan, 2014). Subbituminous coal of economic grade is known from the Neogene and Paleogene sedimentary series (Holdgate et al., 1995).

Aggregates, sand, and gravel are rated up as the premier raw material, followed by quarry and dimension stones, and fifth in the row by lignite and peat (Prentice, 1990; Lorenz, 1991; Lüttig, 2007). In the map illustrating the deposits of fossil fuels, ore, and industrial minerals of Central Europe sand could not be shown. It would have blanked almost the entire map and thus, it was shown in a different one on a regional scale (Dill and Röhling, 2007). The major amount of sand is used as construction raw material. High- and ultra-high purity quartz sands composed of almost 100% SiO₂ required for the production of silica glass, optical, and electronic devices are rare. Although common, these high-silica quartz sands were only rarely investigated on their own with regard to their origin, such as the Sable the Fontainebleau, France (Cojan and Thiry, 1992; Delhaya-Prat et al. 2005).

Areas where high purity white sands are encountered side-by-side with subbituminous coal and peatlands are found on the Falkland Islands at the southeastern tip of South America (Mitchell-Thomé, 1970; Greenway, 1972). According to McAdam and Upson (2010), who gave an overview of the distribution of peatland in the Falkland Islands, about 11408 km², being equal to 93.7 % of the land area are covered with peatland. For the present study the accumulations of organic matter and white sands at the isthmus of the Neck of Saunders

Island (West Falkland Islands) has been taken as reference (Fig. 1).

The scope of the current investigation is: (1) to provide a dataset of siliceous rocks interbedded with coal as to their sedimentary geology, coal petrography, mineralogy and chemistry, including carbon isotopes, (2) to disentangle the genetic relationship between organic matter and sand in a paralic environment under a periglacial regime, (3) to determine the physical-chemical regime in a paralic coal-bearing environment (4) to discuss this environment in comparison with terrigenous shoreline processes in periglacial coal-siliciclastic couples on the northern hemisphere, (5) to model the “natural dressing plant” powered mechanically by marine aquatic and aeolian forces and at an advanced level by chemical processes related to the coal layer.

2. Geological Setting

The on-shore geology of the Falkland Islands is mainly based upon publications of Mitchell-Thomé (1970), Greenway (1972), Aldiss and Edwards (1999) and Clark et al. (1995).

Hydrocarbon exploration ensued studies off-shore Falkland Islands (Richards and Hillier, 2000a, b). Major attention was paid to the geodynamic evolution of the Falkland Island along with the break-up of Gondwana (Mitchell et al. 1986; Marshall, 1994). Remnants of the initial 1.1 Ga old archipelago are met in the Cape Meredith Complex. The sedimentary unit underlying much of the Falkland Islands is the siliciclastic Siluro-Carboniferous Gran Malvina Group, (Fig. 1a). The age of formation of this series is controversial (Greenway, 1972; Stone, 2010). It is overlain by the Permo-Carboniferous Fitzroy Tillite Formation and the sandstones and mudstones of the Lafonia Group (Fig. 1a). Due to their small outcrops Jurassic basic dykes are not shown on the map (Fig. 1a). The arenaceous rocks of the Port Stanley Beds form the bedrocks of the sediments under study exposed in the isthmus of Saunders Islands (Fig. 1b, c). The majority of glacial and interglacial landforms are constrained to the period of

time from 36 ka to 14 ka (Aldiss and Edwards, 1999).

3. Methods

The sampling has been carried out along a transect from the beach to the dune belt encroaching upon the hinterland where the basement rocks are exposed (Fig. 1c). Twelve samples have been taken for investigation of siliciclastic rocks, three each of the zones and 3 for the coal-bearing beds. Radiocarbon dating has been performed on samples taken from the well-bedded coal shown in Figure 2e. Emphasis has been placed upon the mineralogical inventory, since the chemical composition of the clean sands does not change significantly. Examination of thin sections under the petrographic microscope was supplemented by SEM-EDX and X-ray diffraction analysis. No sputter coater was used prior to SEM-EDX analyses because all analyses were carried out under low-vac-chamber conditions (1 to 10 mbar). The technique applied has been supplemented with SEM-WDX. XRD patterns are recorded using a diffractometer with Cu-K α radiation. All samples were powdered prior to analysis. Infrared spectroscopy was carried out in addition to the routine XRD. Only the spectra of the dried pellets are shown. For more information see Russell and Fraser (1994).

Samples were subjected to a grain size analysis apart from sieving the CAMSIZER at a more advanced level. The CAMSIZER® measuring system is based on digital image processing. Prior to the heavy mineral (HM) analysis the samples were sieved and the grain size fraction 63 to 400 μm was used for follow-up HM separation. HM separation was carried out for each sample to the grain size fractions richest in heavy minerals (the 3–4 ϕ fraction) using sodium polytungstate of a density of 2.9 g/cm³ (Callahan, 1987).

Major and trace elements are analyzed by X-ray fluorescence spectrometry (XRF). Samples are prepared by mixing with a flux material and melting into glass beads. The beads are

analyzed by wavelength dispersive X-ray fluorescence spectrometry (WD-XRF). To determine loss on ignition (LOI) 1000 mg of sample material are heated to 1030 °C for 10 min.

Radio-carbon dating was carried out in the conventional way as described by Geyh and Schleicher (1990). The conventional ^{14}C age data were calculated based on the LIBBY half-life period (5568 years) and by calibration to the NBS oxalic acid standard adjusted to the internationally used radiocarbon timescale.

The coal petrographic investigations included different steps. The preparation of polished particulate block was conducted by LAOP, Tübingen, following the German Standard Methods DIN 22020-2: 1998 and the guidelines published in Taylor et al. (1998). Random huminite reflectance measurements were carried out in accordance to German National Standard DIN 22020-5: 2005, in non-polarized light, at magnification of 500 $\times$ and room temperature of 23 °C $\pm$ 1 °C using a Leica DMRX incident-light microscope equipped with a MPV Compact 2 microphotometer photomultiplier tube (PMT), halogen lamp (12 V, 100 W), HBO® Lamp (103 W/2, 12 V), and Leica Oil P 50 $\times$ /0.85 oil immersion objective. Leica Type F immersion oil $n_e = 1.518$ (23 °C) as well as synthetic mineral standard (0.423) were used for the purpose of reflectance calibration. 100 reflectance measurements were performed on the lignite sample using Leica MPV Meas software. Filters used for analysis in blue fluorescence light are Leica excitation filter BP 355–425, dichroic mirror RKP 455, and barrier filter LP 460. Photomicrographs taken in incident bright and blue light excitation using a Leica digital fluorescence camera DC 300 F at format of 1.300 $\times$ 1030 pixels were stored using imaging software Image Access Premium 09. The maceral nomenclature used in this paper follows ICCP System 1994, as it is adopted by the International Committee for Coal and Organic Petrology (ICCP, 2001; Sýkorová, 2005; Pickel, 2017).

4. Results

4.1 Geology

The lithology of the coal-and-sand unit is illustrated by a sequence of five zones, each with typical site images taken along an idealized transect from the upper shoreface to the hinterland, where the bedrocks crop out (Fig. 2). The mean low water level marks the boundary between the upper shoreface and lower foreshore in this microtidal regime (< 2 m) (Davies, 1964; Hayes, 1979; Kennedy and Milkins, 2015) (Fig. 2). White fine-grained high-purity quartz sand makes up the flat foreshore with its foreset lamellae dipping seaward at very low angle (antidunes). Towards the top they are terminated by aeolian ripples (Fig. 2a). On steeper parts gravel bands terminate the upper backshore sand against the dune belt (Fig. 2b). The flat pebbles and gravels display an imbricate arrangement, dipping towards the sea, where the breakers come from. These coarse unconsolidated sediments mark the storm water level (Fig. 2c). They form, locally, pavements at the foot of the subbituminous coal layer, undergoing strong winnowing and resulting in gravel topped “sand towers”, which stand out from the beach platform (Fig. 2c). Large dunes are arranged one after the other resulting in the dune belt (Fig. 2d). The well bedded, mineral-rich subbituminous coal layer lies within the dune belt, measuring approx. 1 m in thickness (Fig. 2e, f). Underneath and within, ferroan fine-grained sandstones with goethite cement exists (Fig. 2e). Two different types of polygonal frost pattern of the ground occur on top of the coal layer (Fig. 2f, g). Where overburden is stripped off, the polygonal frost pattern ground evolved immediately on the denudated coal layer, whereas at the NW and SE end of the strand plain less well-expressed, large polygons evolved in the vegetated podzolic topsoil on the coal layer (Fig. 2h). The terminology of the periglacial features follows the suggestions of French (2007). The most conspicuous part of this cross section is the cliff of quartzites standing out from the ridge whose gentle dipping slopes are strewn with boulders and gravel of the same lithology

(Fig. 2i).

4.2 Sedimentary petrography

The mineral assemblage of the coal-and-sand unit can be subdivided into the heavy mineral suite (section 4.2.1) and the light minerals plus phyllosilicates, some of which such as the Fe-Mg chlorites are heavy minerals by definition but treated in section 4.2.2 for genetic reasons (Table 1).

4.2.1 Allogenic heavy minerals

Not surprisingly, in these white quartz sands the heavy mineral contents are very low and predominantly composed of allogenic heavy minerals. From zone I through zone IV the heavy minerals steadily increase from 0.05 wt. % to 2.00 wt. % (Table 1). In the succeeding paragraphs the heavy minerals are categorized and dealt with according to the order of decreasing stability (Morton, 1984; Morton and Hallsworth, 1999).

Zircon-rutile-tourmaline. Among the detrital or allogenic heavy minerals the ultrastable heavy minerals zircon and rutile prevail. Zircon rarely occurs in subhedral or even euhedral crystals and often appears in fragments still intergrown with quartz. The same holds true for rutile. Tourmaline is very seldom, and no special types of intergrowth or grain morphologies can be reported for this B silicate.

Garnet-spinel: Garnet pertains to the group of minerals being placed in the middle of the chart of heavy minerals with regard to their vulnerability of weathering. In view of this vulnerability well-shaped garnet crystals cannot be expected. The prevailing members of the garnet s.s.s.(= solid solution series) are dominated by almandine and pyrope with little amounts of grossularite. The common spinel is more resistant to abrasion than the overall minerals, where it comes next to rutile in the stability charts, but despite this prominent position it is only scanty in the heavy mineral assemblage of zones III and IV.

Monazite-xenotime-sphene: The REE phosphates monazite and xenotime are present in zone III. The most common phosphate apatite which is slightly more vulnerable to weathering than the afore-mentioned REE phosphates is absent, whereas sphene which also belongs to the group of moderately resistant minerals is present, but as a rare constituent.

Amphibole-clinopyroxene: Both mafic minerals are known to be a rather labile against weathering. As a consequence, their crystal morphology is poorly preserved.

Barite-celestite: Ba and Sr sulfates are rather uncommon heavy minerals, not only in this environment. Locally, celestite lumps are associated with chalcopyrite in the samples under study.

Iron-titanium oxides: The Fe oxides magnetite, hematite, goethite, and the semiopaque ilmenite are only sporadically observed in the heavy mineral suite. While the Fe oxides are left unaltered, the Fe-Ti oxide is replaced by “leucoxene”, a mineral aggregate of anatase, pseudorutile, and Fe oxide hydrates. Much has been published about the alteration of ilmenite and the resultant mineral pseudorutile, also called arizonite or hydroilmenite. The latter are still under dispute as to their credibility as a mineral of their own (Grey et al., 1994; Pe-Piper et al. 2005). Therefore the term “leucoxene” is more appropriate in this case.

4.2.2 Authigenic heavy minerals

Authigenic minerals which immediately can contribute to the environmental reconstruction, hence, deserve more attention than the detrital heavy minerals. They may shed some light only in an indirect way on the physical-chemical regime and consequently are shown in a set of micrographs (Fig. 3).

Fe-Cu sulfides- Fe carbonate: Spherical framboidal concretions are common to zone I (Fig. 3a). All aggregates contain pyrite crystals intimately intergrown with each other and dominated by the octahedron in combination with the cube which merely bevel the apices of the octahedron ((111) > { 100}) (Fig. 3a). The second morphological type also contains

octahedral crystals but the majority of grains have to be denominated as “framed hexahedra” of pyrite caused by secondary pyrite growing homoepitactically along the edges of a host pyrite (Fig. 3b). Minute grains of Fe-bearing carbonate, probably siderite, are also encountered in this zone I (Table 1). The only Cu sulfide identified in the samples is chalcopyrite. It does not occur as individual crystal or in mono-crystalline sulfide aggregates but only as inclusion sheltered by celestite.

Aluminum-phosphate sulfate: The alunite supergroup also abbreviated to APS is a very complex group of minerals consisting of more than 40 end member types (Jambor, 1999; Dill, 2001). The only representative, exclusive to zone IV, is florencite-(Ce) a LREE-bearing aluminum phosphate $[\text{CeAl}_3(\text{PO}_4)_2(\text{OH})_6]$, which occurs in clusters of pseudocubic crystals (Fig. 3c). It is accompanied by quartz and diatoms (Fig. 3d).

4.2.3 Light minerals

Tectosilicates: The most frequent mineral is quartz, present mainly as detrital grains, seldom as silica (chalcedony) or floral remains (Fig. 3d). Second in abundance are alkaline feldspars, microcline and ordered albite. Both mineral groups are present from zone I though zone IV.

Carbonate minerals, sulfates and halogenides: Calcite and dolomite are only sporadic in zones I, III, and IV. This is also valid for halite and gypsum (Table 1).

4.2.4 Phyllosilicates

Phyllosilicates are not very widespread in the arenaceous sediment from zones I through IV (Table 1). No argillaceous beds are interbedded with the sandy beds and in the coal layer, proper, the ash yield of which is high due to the increased arenaceous siliciclastics. Nevertheless the great variety of sheet silicates can be of assistance to constrain the environment of deposition of these coal-bearing siliciclastics (Fig. 4a, b, Table 1).

7-angstrom phyllosilicates: IR analysis proved that the samples contain at least traces of a

kaolinite-group mineral. They are present in zones I and IV, yet in different quantities and types (Fig. 4b). In zone I the common 7-angstrom phyllosilicate kaolinite is present in significant amounts (Russel and Fraser, 1994). Considering the absence of the bands diagnostic for kaolinite and the presence of a shoulder at about 3600 cm^{-1} suggests the presence of a Fe-rich halloysite in zone IV. Halloysite has a similar chemical composition as kaolinite but contains additional water molecules between the layers, leading to the formula $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \cdot 2\text{H}_2\text{O}$ in its fully hydrated form. In the kaolinite polymorphs the water content stands at 13.96 wt. % H_2O , in halloysite it is higher and lies in the range from 14.3 wt. % to 15.35 wt. % H_2O (Weaver, 1989). The halloysite-(10 Å) typically accommodates interlayer water which distinguishes it from the other kaolinite-group polymorphs and irreversibly dehydrates to a 7 Å structure (Joussein et al., 2005; Churchman et al., 2010).

10- and 14- angstroem phyllosilicates: The band at 3630 cm^{-1} proves the presence of dioctahedral clay minerals such as illite, muscovite, or smectite. Muscovite occurs as muscovite 3 T. Smectite is not present in one of its end-member types, e.g., nontronite, but present only in form of irregular illite-smectite mixed-layers in zone I. Chlorite occurs as Fe-Mg chlorite.

4.2.5 Granulometric and morphometric analyses

Table 1 shows a slight seaward increase of the median from fine sand to fine- to medium sand. The sorting coefficient does not vary considerably and the overall assessment comes to the conclusion of a well sorted siliciclastic host rock series. The measurements of the grain-size distributions by Visser (1969) along the South Carolina Coast and the plotting of the data as log-probability curves were among the first attempts to significantly contribute to the facies analysis of clastic sediments. In the present geological setting, quartz, a mineral known for its poor cleavage and its high rank in the Moh's hardness classification scheme,

is abundant. Two sedimentary features of the quartz sand are determined and plotted versus each other: (1) sphericity of the grain, (2) size of the grain (Fig. 5). The facies zones I, II, and III can be distinguished by their different trends in terms of grain size and morphology, which are indicative of different depositional processes (see section “Discussion”) (Fig. 5).

4.3 Sediment chemistry

The chemical composition of the siliciclastic rocks under study in the Falkland Archipelago furnishes evidence of a high-purity quartz sand unit (Table 2a, b). The composition is on display in Table 2a as compared to similar depositional environments and climatic regimes elsewhere. In Suriname and Borneo, Malaysia, coastal marine coal-bearing series evolved under humid tropical climatic conditions, in Manitoba glacial-fluvial arenaceous series were pitted for glass sand under periglacial conditions in Arctic Canada (Watson, 1985; Lorenz and Gwosdz, 1999; Hutchinson, 2005; Wong et al., 2009). Irrespective of the climatic conditions in the study sites, the quartz sands from the coastal marine coal-bearing series closely resemble each other. The periglacial sands, however, strongly contrast with the overall white sands with regard to their poor silica contents and increased amounts of impurities such as Al, Fe, and Mg etc. (Table 2). Considering the trace element contents of the sands under study, there is only Zr, Ba, and Sr which warrant mentioning for their elevated values: Zr (min: 61.0, mean: 183.7, max: 404.0), Ba (min: 63.0, mean: 67.3, max: 90.0), Sr (min: 9.0, mean: 17.3, max: 37.0) (Table 2b). The corresponding host minerals zircon, barite, and celestite are listed in Table 1.

4.4 Coal petrography and age dating

There are two facies zones, in which organic matter can be identified by mineralogical or coal petrographic techniques. The most interesting features of the IR spectra $< 2000\text{ cm}^{-1}$ are the significant contents of dispersed organic matter in zone I (lower foreshore adjacent to

shoreface) and the presence of coaly matter in zone IV within the dune belt, where subbituminous coal layer crop out (Table 1, Fig. 2). The latter facies zone is subjected to a detailed coal petrographic study in the succeeding sections. No coal quality parameters were determined because this small exposure of coal relative to the vast amount of peatland is not economic. Equivalent data have only been reported for the Falkland peat by Greenway (1972). The average calorific value of samples from the Falkland Islands is 7800 B.T.U. at 26 % moisture content and corresponds to 18174 kJ/kg.

4.4.1 Huminite reflectance

Random huminite (vitrinite) reflectance value of the investigated sample is shown in Table 3. The obtained reflectance value of 0.38% R_r indicates a “Braunkohle” in accordance to DIN Norm 22005-2: 1989-08 and “Weichbraunkohle” following Pohl (1992). After ECE-UN (1998) coal classification, the examined sample is classified as low-rank coal or ortho-lignite, providing the gross-calorific values ≤ 20 MJ/kg (on moist, ash-free basis).

4.4.2 Maceral composition

Micropetrographic observations show a predominance of huminite over liptinite, inertinite, and mineral matter (Fig. 6). The gelification process has reached an advanced stage, since the observed amount of ungelified telohuminite (textinite) is minor. Textinite is well-preserved (Fig. 6a, d). Detrohuminite in the form of densinite predominates in the huminite maceral group (Fig. 6a, b). Also vascular tissues with sieve plates and fibers are common, exhibiting yellowish fluorescence. Inertinite is present in the form of fusinite, semifusinite, macrinite, inertodetrinite, and chars with fusinite and semi-fusinite representing dominant inertinite macerals (Fig. 6c). Fusinite and semi-fusinite are often fractured and fragmented. Inertodetrinite is usually associated with densinite. Liptinite is the second most abundant maceral group and comprise mainly cutinite, sporinite, and liptodetrinite (Fig. 6e, f).

Suberinite appears in traces and is characterized by pale yellow fluorescence. Cutinite usually occurs as well-preserved thin walled cutinite. Preserved algal remains (telalginite) are extreme rare.

4.4.3 Carbon isotope studies

Radiocarbon dating of coal-bearing samples of fine-grained sand yielded an age interval from 1055 to 1275 AD with $\delta^{13}\text{C}$ of -26.6 ‰. The latter carbon isotope data are typical of peat and subbituminous coal of Cenozoic age (Bechtel et al., 2008).

5. Discussion

5.1 The environment of deposition and classification

There are several papers dealing with coal formation, also including the depositional environment of the mire. No individual studies are cited in the current paper. Three textbooks are thought representative of the different approaches taken in these publications instead. Galloway and Hobday (1983) describe the terrigenous clastic depositional systems in the classical sedimentological way adding an appendix dealing with clastic environments relevant for fossil fuels. Diessel (2012) looks at the environment from the coal petrographer's point of view but integrating the various sedimentological and in parts mineralogical features relevant to coal formation. Pohl's textbook (2011) lies at the opposite end of this chain with a strong impact on the economic aspects of coal. Diessel (2012) also used the physiographic features of a micro-to mesotidal wave-dominated non-barred linear shoreline and discussed them in context with the Late Paleozoic Newcastle Coal Measures and Waratah Sandstone, Australia. A similar scenario can be found in the site under study from the Falkland Archipelago. The current site is a modern Quaternary analogue which is, however, not economic as to coal. It can, however, be used in parts as an exploration model for the fossil fuel and for the non-metallic part of the area under study, in other words, for high-purity

quartz sands.

5.2 The physical-chemical regime of the environment of deposition

5.2.1 Foreshore

The foreshore lies below the high-water level and is representative of the swash zone from the hydrodynamic point of view. It is fully marine as to the sedimentary processes an interpretation conspicuously reflected by the granulometric and morphological results (Fig. 5a). Figure 5 is indicative of a gradual, landwards directed change of marine processes devoid of point-source continental environments such as a delta or estuary. The foreshore has organic material only near the shoreface/ low water level. Framboidal pyrite and siderite (?) are clear markers for a prevalently reducing environment, which becomes more oxidizing moving landward (Fig. 2a, 3a, b; Table 1). The pH range and activities can be concluded from the heavy and light minerals (Fig. 7, Table 1). Kaolinite is crucial as to the silica and aluminum activities in the system; it is stable at a $\text{Log } a_{(\text{Al}^{+++})/(\text{H}^+)^3} > 7.5$ and $\text{Log } a_{\text{SiO}_2(\text{aq})} > -4$. Below that boundaries silica and gibbsite, respectively, would form instead (Fig. 7a, b). As to the pH, kaolinite can form over the entire pH range below $\text{pH} < 7$. The coexisting illite-smectite mixed-layers, however constrain the stability field, so that a pH range between 6.5 and 7 is realistic and the system called neutral to mildly acidic. Chlorite s.s.s. and feldspar are weathering relics left over after transport from the nearby hinterland into the coastal environment. The presence of heavy minerals of intermediate to low stability against weathering well agrees with these interpretations.

5.2.2 Backshore plus dune belt

Considering the redox conditions in this zone, we have to deal with two different sub-environments, strongly contrasting with each other. The footwall backshore and hanging wall dune sediments developed under $\text{Eh} > 0$, whereas the coal layer has a $\text{Eh} < 0$ (Table 1). As

far as the kaolinite group minerals are concerned we can use in parts the data figured out in section 5.2.1. There is a mineral decisive for the existing pH. Florencite can be approximated as to its stability field by the mineral alunite in Fig. 6b. It is stable in the range pH 5 to pH 1. McAdam and Upson (2010) characterize the modern soil on top of the coal seam as “shallow, acid (pH 4-5), infertile, and undeveloped” . The reported pH range seems to be a realistic one for the oxidizing parts of the backshore and vegetated fossil part of the dune belt which is blanked with acid grassland and dwarf shrub oceanic heath. The cartoon in Fig. 2 shows the pH and Eh variation along transect perpendicular to the shoreline.

The coal petrographic investigations also contribute to the clarification of the physical-chemical regime in the study area. Time-dependent models of organic metamorphism indicate that % Rr increase primarily in response to burial temperatures (Barker, 1989; Barker et al., 1991). Thus, vitrinite reflectance can serve as an indicator of paleotemperatures. Several statistical correlations with relevant equations exist between % Rr and peak paleotemperatures (Barker 1983, 1988; Price, 1983; Barker and Pawlewicz, 1986, 1994). The authors believe that the equation $T(^{\circ}\text{C}) = 148 + 104 \{\ln(Rr)\}$ (Barker, 1983) is the most conservative among the time-independent equations, yielding the lowest paleotemperature estimate for the obtained huminite (vitrinite) reflectance value. Following Underwood et al. (1993) the estimates of paleotemperature should be rounded to the nearest 10 °C. According to the equation for the paleotemperature estimates, the measured random huminite (vitrinite) reflectance value correspond to peak-paleotemperatures of 47 °C and is rounded up to 50 °C. If we assume that palaeogeothermal gradients were similar to the present day values of 4.4 °C/100 m reported by Richards and Hillier (2000a,b) for the North Falkland Basin and 7.4 °C/100 m reported by Langseth and Ludwig (2007) for the Falklands Plateau, the examined lignite sample would have been buried to a depth ranging from about 0.7 km to 1.1 km. This is a temperature-pressure regime which does not accord with the

environment describe in Table 1.

5.3 Provenance and source analyses of the coastal coal-sand unit

The most effective clue to disentangle the provenance of siliciclastic sediments lies within the heavy mineral community which in spite of its scarcity is rather variegated and points to a dual- source origin (Table 1). The stable and ultrastable heavy minerals such as zircon, rutile, garnet and monazite have been derived from the Gran Malvina Group. The less stable heavy minerals amphibole can hardly be linked with these Paleozoic rocks. There is amphibole in lamprophyre dykes intersecting the Precambrian Cape Meridith Complex which were dated by Cingolani and Varela (1976) to 554 ± 25 Ma and 496 ± 15 Ma. Hards (1997) recorded strongly altered dyke rocks of doleritic composition with pyroxene at Saunders Island Neck. These dyke rocks belong to the Jurassic igneous magmatic suite which denotes the break apart of Gondwana.

A different way to pinpoint the source of sediments is provided by the huminite reflectance measurements (section 4.4.1). Values of 0.38% R_r attesting to an overburden measuring between 0.7 km and 1.1 km do not agree with the overall sedimentary setting of the Quaternary coastal sediments. The coal developed during the Neogene or Paleogene. According to Aldiss and Edwards (1999) no Mesozoic and Cenozoic sediments have been discovered on the Falkland Islands. Macphail and Cantrill (2006) found pollen and spore assemblages (microfloras) well-preserved in organic clays and coaly sediments associated with fossil tree remains in the Forest Bed of West Point Islands, which is situated not far off the study area (Fig. 1a). The authors did not only describe and interpret the floral remains but also concluded the age of formation to be in the range Oligocene through late Miocene. This is an interval for which no sediments are known on-shore the Falkland Islands but equivalent strata were drilled in the off-shore basins (Barker et al., 1991; Cunningham et al., 1998).

There are many investigations, among others by Christanis (2004) which reported R_o values. They well accord with values from the Miocene lignite deposits. Even if this not precise tool to date accumulations of organic matter, it may give an idea of the age of the Falkland coal layer. Accordingly, the coal beds are well-bedded within the Quaternary dune belt attesting to transport and deposition of light and heavy minerals together with the Oligocene through late Miocene organic material (Fig. 2c, e). The coal-bearing sediments are allochthonous of terrestrial origin with a brackish-marine influence.

5.4 The subbituminous coal-sand unit within the catena of paralic coal-bearing environments.

Paralic coal-bearing formations are very widespread during the geological past. They are typical of, e.g., the Carboniferous Coal Measures in many parts of Europe, where these units are representative of alternating marine and continental terrigenous beds. The various linear marine shoreline subenvironments, which occur at a coast undergoing transgression, have been studied among others in detail by Boyd et al. (1992) who categorized them as a function of increasing tidal power and increasing wave power (Fig. 8). The opposite regressive scenario along a linear shoreline, interrupted often by point-source depositional systems such as fluvial-dominated "bird-foot deltas (e.g. Mississippi Delta) have been omitted in Fig. 8. These regressive subenvironments are not discussed here, because the retreat of the ice after the Glacial Period implies not only melting of ice but also a rising sea level in many parts of the globe and consequently a transgressive regime. The various sedimentological processes and the geomorphological features of this peculiar coastal environment between land and sea are dealt with in the comprehensive papers by Hayes (1979), Dalrymple (2010), Dalrymple and Choi (2007), Davis and Dalrymple (2011), Longhitano et al. (2012), and Hayes and FitzGerald (2013). Their ideas have found recognition in the cartoon of Fig. 8 and in the reference examples selected from the northern

hemisphere. Figure 9 illustrates coal- and peat-bearing paralic series after the retreat of the inland ice in Scandinavia, which is a mirror image of an erosional environment on the Falkland Islands. The current study area of the Falkland Archipelago is located on the right-hand side of this environmental catena typical of a linear terrigenous shoreline, where the wave power is high and the tidal range moderate (Fig. 8a). It lies near the boundary between the microtidal and the micro-(meso) tidal compartment, which is characterized by a sealed-off lagoon intercalated between a seaward sandy barrier island and marshes on the landward side (Fig. 8a, b).

5.5 The periglacial subbituminous coal-sand unit from the southern hemisphere in comparison to those from the northern hemisphere

The periglacial environment under study on the southern hemisphere in the Falklands has also equivalent environments to compare with for their coal/ peat-bearing lithologies, as well as marine and periglacial terrigenous sediments in the German Bight (Fig. 9a). The southern and eastern shoreline of the North Sea is called the Wadden Sea. It stretches for almost 1000 km from the eastern Netherlands to Denmark and reflects all features of a macrotidal through microtidal coast (Flemming and Davis, 1992) (Fig. 9). The tidal range increases from the W and from the N from 1.5 m and 1.0 m, respectively, to 4 m in the estuary of the German Bight NW of Hamburg. Along this profile all the hallmarks are illustrated in the cartoon of Fig. 8. Two sites have been selected for comparison. The subbituminous coal seam along the coast of western Denmark is embedded into cross-bedded aeolian sands of the dune belt in a microtidal environment (Fig. 8a, 9b). The seam overlies a seat earth similar to what has been reported from the southern hemisphere, however, it does not show any signs of polygonal frost pattern of the ground on top. Glacial till is present underneath. Near Easterholt, Denmark, a sequence resembling that from the Falklands has been investigated by Wagner and Koch (1974) (Fig. 9a). Eighteen meters below ground a lignite seam was

exploited. Its roof rocks made up of fluvial quartz sand are penetrated by rootlets and show periglacial structures as a result of strong cryoturbation – see for comparison Fig. 2g and 2h open and concealed periglacial structures. It is overlain by another sequence of Quaternary glacial-fluvial sandy and gravelly sediments with ventifacts and aeolian sands – see for comparison Fig. 2d. In the reference sites from the northern hemisphere, a more or less continuous stratigraphic sequence exists from the Late Paleozoic through the Quaternary. The accumulation of the organic matter is autochthonous. By contrast, in the Falkland Islands we are faced with a hiatus from the Paleozoic through the Quaternary giving host to allochthonous accumulation of organic matter. The subbituminous coal in Denmark is Neogene in age (Friis, 1979; Rasmussen et al., 2006). Stephan (2014) recorded lignite-like accumulations of organic matter to be interbedded with white sands also from the early Pleistocene in northern Germany enveloped on one side by the North Sea and on the opposite one by the Baltic Sea. Coal petrographic investigations are missing from the above mentioned subbituminous coals.

A shallow drill hole penetrated sediments of a mesotidal hydrographic regime (Fig. 9a, c). There are also aeolian dune sands, which are overlain by a podzolic soil, revealing a tripartite subdivision into the horizons A_e (bleached eluvial topsoil horizon), B_h (illuvial horizon enriched in humic matter), and B_s (illuvial horizon enriched in Fe and Al). In geochronologically younger positions the peatland follows (Fig. 9c). Unlike the site “b” in Fig. 9 and the site under study on the Falkland Islands, the topmost sediment is argillaceous in grain size as may be expected in a mesotidal mud flat, succeeded seaward by the barrier island (Fig. 8b). In the southern coast of the North Sea, no coherent barrier island exists. It was broken apart into different isolated islands by some inlets. The Holocene peat horizons are linked with the vast peat bogs of the mainland in northern Germany.

Coal facies studies are focusing on different lithologies bearing organic matter. Mesozoic and Tertiary lignite deposits from the eastern United States are presented in great detail by Hower and Eble (2004). Hackley et al. (2010) studied the subbituminous carbonaceous shale from Afghanistan while Christanis (2004) provided an overview of the various facies types of Neogene and Quaternary lignite deposits in Greece. The lignite studied in the Falklands has been derived from peatland with possibly periodic flooding by brackish waters or seawater. Taking into account that the majority of the peat: lignite compaction ratios for various lignite range from 2:1 to 4:1 as reported by Widera (2015), it can be assumed that the peat thickness prior to burial was 2-4 times greater than today. The observed vascular tissues with sieve plates and fibers are considered here to represent primary vascular tissue, most possibly of herbaceous angiosperms. The organic matter in the well bedded lignite seam has been affected by open and concealed cryoturbation (Fig. 2e, g, h).

One can envisage that the subbituminous coal layer came into existence during the early Pleistocene and has been affected by the last glacial progradation, which is said to have been lasted from 15000 to 25000 years ago (Aldiss and Edwards, 1999). While its organic matter formed during a warmer Neogene period, its outward appearance and structures are affected by coastal marine and periglacial processes. The radio-carbon age data 1055 to 1275 AD are indicative of a post-glacial dissection of the isthmus as a result of a rising sea level and formation of organic matter (Fig. 1c). Similar erosive processes are also common to the southern and eastern coast of the German Bight leading there to the break-up of a coherent sandy barrier into individual barrier islands along the coast of the Wadden Sea (Fig. 9a) (Flemming and Davis, 1992). A similar destruction is in the making at Saunders Island, where the isthmus is going to be cut through resulting at the very end in the formation of two separate islands and the disappearance of the lignite seam (Fig. 1c).

5.6 Paralic coal systems- a natural dressing plant for high-purity quartz sand

Harben and Kužvart (1996) provided an outline of high-purity quartz sands or in sedimentological terms, quartz arenites, some of which are listed in Table 2. Pettijohn (2013) cited experimental studies and concluded: „...it seems improbable that a quartz arenite sand of the kind found in the geological record could ever be produced by river transport no matter how prolonged”. In other words, it has to go through a natural dressing plant like that exemplified on the Falkland Islands, with the last and most effective chemical module coal (peat) (Fig. 10).

Quartzose rocks such as quartz sandstone, quartzite quartz gneiss are no prerequisite for the “mill feed” to the natural dressing plant but nevertheless held to be the most favorable source rocks (Fig. 10). The Port Stanley Beds are such an excellent source rock (Fig. 1b, c). They were exposed to a large extent near the coast and reworked in a microtidal regime where the wave power reaches its maximum in the hydrodynamic surf and swash zones, which are equivalent to the shoreface and foreshore (Fig. 2).

In this first stage of mineral dressing the grain size is reduced mechanically to the level of a medium to fine sand (Table 1). Beach or foreshore sands are well sorted with sorting values of between 0.35 to 0.50 (ϕ units). For comparison, glacial-fluvial settings have sands with sorting values of between 1.40 to 2.60 and higher (ϕ units), ranked very to extremely poorly sorted, whereas common river sands are moderately to moderately well sorted with sorting values of between 0.50 to 1.40 (ϕ units), (Friedman et al., 1992). There is also a separation taking place according to the specific gravity, in that the amount of heavy minerals is reduced (Table 1).

In the second stage of mechanical mineral dressing the wind and water rework together the

sand and according to the chart of sorting elaborated by Friedman et al. (1992) the sands become very well sorted with values of < 0.35 (ϕ units), whereas the morphology of grains gradually approaches the sphere (Fig. 5c). The content of heavy minerals increases in the backshore or near the dune belt (Table 1). Such peculiar types are of utmost importance in the petroleum industry as proppant sands, which should be of well-rounded grain shape, with a solubility in HCl < 0.3 % so as to be capable of opening or keeping open the reservoir rock of oil and gas wells.

In the third stage chemical leaching promoted by organic acids destroyed the labile constituents of the arenites such as feldspar group minerals, carbonates minerals, and calcareous tests of faunal remains (Fig. 10). Evidence for organic acids percolating within the subbituminous coal layer and trickling out of it into the footwall sand is provided by ferruginous sandstones (Fig. 2e- inset). The shift in the pH value is a clear indication for the effectiveness of this leaching process, which does not allow the above minerals to be preserved. It is the part where inorganic sediments get in touch with organic ones namely coal/ peat (Fig. 2, 8a). In the microtidal setting the processes interacted most effectively. Moving towards environments dominated more and more by the tidal power sees sites of accumulation of coal and sand to split apart, e.g., the back-barrier lagoon and the wave-dominated estuary (Fig. 8b, c). In the tide-dominated estuary and the tidal flats, organic matter is very widespread as coal/ peat. Sand is preserved or replaced by mud and the wave power is too moderate to speak any longer of a mechanical tool of a natural dressing plant for sand (Fig. 8d,e). Even if the mechanical tool of the natural dressing plant no longer exists in this environment, the chemical tool provided by the subbituminous coal did not lose anything of its leaching capacity. It has been presented here for the sake of completeness of the “natural dressing plant run by coal” illustrated in Fig. 8 but providing full particulars would go far beyond the scope of the current study. The reader is referred to the review of kaolin by

Dill (2016) and the particular treatment of the couple coal-kaolin by Dill et al. (2008b). Three images have been selected to show the tidal-dominated coal-bearing environment. Kaolin is representative of this argillaceous commodity being upgraded in terms of quality by the interbedded subbituminous coal under acidic conditions and may exemplify the opposite end of the natural processing plant driven by the tidal and wave powers (Fig. 8, 11, Table 1).

6. Conclusions

The superficial Quaternary sediments resting unconformably on the Paleozoic basement rocks are made up of subbituminous coal and white, clean sands. Both are genetically interrelated with each other by what might be called metaphorically a “natural dressing plant” (Fig. 1, 2, 10). The coal-sand couple evolved during 6 discrete stages.

Stage I: The detrital parent material has been derived to a large extent from the quartzose siliciclastic rocks of the Siluro-Devonian Gran Malvina Group. Its quartzites and sandstones were laid down in a fluvial to marine environment. They act as some kind of sandy proto-ore for the present-day white sand.

Stage II: Although no sedimentary record exists from the early Mesozoic to the late Neogene on the Falkland Islands there are indirect markers for the climate and the depositional environment. From the Oligocene through the late Miocene under a warm tropical climate organic matter was accumulated in a paralic environment to form the subbituminous coal under study. It is the chemical agent to upgrade the quality of the silica sand (Fig. 10).

Stage III: During the Pleistocene coastal-marine erosional and depositional processes in a wave-dominated regime gave rise to the built-up of the coal-sand unit. Near-shore marine reworking led to the enhancement of the quartzose sand (Fig. 2, 10). Mineral dressing was mechanically, powered by the wave energy of a microtidal hydrodynamic regime in the shoreface and foreshore subenvironments. It reduced the grain size to the level of a medium

to fine sand, enhanced the sorting coefficient and contributed to the separation of minerals according to their specific gravity (Table 1).

Stage IV: The subbituminous coal layer has been reworked at least during the last glacial progradation dated back between 15000 to 25000 years; this has stripped the overburden. The atmospheric processes exerted an unimpeded access to the coal, causing podzolic soils and peat to develop on top.

Stage V: This stage is a repetition of what has been recorded from stage III as to the mechanical part of mineral beneficiation. It was also mechanical in essence. Wind and water agents rework together the sand along the backshore and in the dune belt, causing: (1) the morphology of grains to gradually approximate the shape of a sphere (Fig. 5c) and (2) the content of heavy minerals to increase in the backshore near the dune belt (Table 1).

Stage VI: In this stage the mechanical part of the natural dressing plant is substituted for by the chemical leaching, which is promoted by organic acids derived from the coal/peat. They affected the labile constituents of arenites such as feldspar group minerals, carbonates minerals, and calcareous tests of faunal remains (Fig. 10). The shift in the pH is a clear indication for the effective leaching process, which does not allow the above minerals to be preserved. It is the part of the sedimentary section, where inorganic sediments get in contact with organic sediments coal/ peat (Fig. 2, 8a). This chemical alteration was grinded to a halt by another sea level rise starting from around 1055 to 1275 AD (Fig. 2e). It gradually destroyed the coal layer and at the very end will cause the isthmus, called "The Neck", to disappear completely (Fig. 1c)

While the depositional environment, as the most effective regime for the processing of sand is located in the microtidal setting, where coal and sand interacted together most closely, its capability diminishes towards environments dominated by the tidal power, e.g., the back-barrier lagoon and the wave-dominated estuary (Fig. 8b, c). In this part the mechanical tool of the natural dressing plant no longer exists due to the hydrodynamic regime. The chemical

tool provided by the subbituminous coal layer become the only efficacious one (Fig. 8). In the macrotidal regime, where argillaceous sediments are more prevailing, the acidic physical chemical regime created by the organic acids trickling out of the subbituminous coal are the only and most effective way to improved the quality of clay and contribute to the build-up of kaolin deposits.

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Captions

Fig. 1 The geological setting of the study side on the Falkland Islands/ Islas Malvinas modified from Mitchell-Thomé (1970) and Greenway (1972).

- a) Geological overview of the Falkland Islands/ Islas Malvinas.
- b) Geological overview of Saunders Islands/ Isla Trinidad.
- c) Geological and lithological setting of the Isthmus ("Neck") of Saunders Islands/ Isla Trinidad.

Fig. 2 The lithology of the subbituminous coal-and-sand unit illustrated by site images along an idealized transect from the upper shoreface through to the hinterland with outcrops of the bedrock (Port Stanley Beds) at Saunders Island, unless stated otherwise. The redox- and pH regime are displayed (for more details see Table 1). The transect is localized in Fig. 1c. The Eh in the various environments and the ages of formation are given in *italics* (Neogene = autochthonous coal now reworked) .

- a) Fine-grained high-purity quartz sand on a quite flat foreshore with foreset lamellae dipping at very low angle seaward (antidunes), terminated by aeolian ripples (upper left). The dark brown flakes are wind strewn seaweed. Height of crossbed-set ca. 20 cm.
- b) Gravel band terminating the upper backshore against the dune belt. The flat pebbles and gravels display an imbricate arrangement dipping towards the sea where the breakers come

from. Carcass Island Leopard Beach.

- c) Gravel pavement followed inland by the coal layer. (c). Strong winnowing and gravel on top of “sand towers”.
- d) Dune belt terminating the beach towards land at Carcass Island Leopard Beach.
- e) Cross section through a coal layer of mineral-rich subbituminous coal (thickness approx. 1 m). The inset shows a fine-grained well-sorted brown sand cemented by goethite reflecting the intrastratal solutions in the coal and its immediate footwall rocks.
- f) Well-bedded subbituminous coal layer. Side of the sampling bag for scale measuring ca. 15 cm.
- g) Polygonal frost pattern of the ground on top of the exposed/ denudated coal layer. See sample bag for scale in one of the large polygons.
- h) Polygonal frost pattern ground on top of the coal seam overlain by a thin podzolic soil and grassland.
- i) Cliff of quartzite standing out from the ridge whose gentle dipping slopes are strewn with boulders and gravel (Port Stanley Beds) .

Fig. 3 Authigenic heavy minerals in the coastal marine sediments in micrographs of the SEM (back-scattered electron images).

- a) Framboidal pyrite clusters in zone I.
- b) Clusters of framed hexahedra of pyrite in zone I.
- c) Clusters of pseudocubic crystals of florencite-(Ce) in zone IV.
- d) Aggregates of florencite-(Ce) surrounded by quartz grains and diatoms in zone IV.

Fig. 4 Reference graphs to display the XRD and IR spectra of clay minerals in the study area.

- a) XRD (x-ray diffraction) run with major reflections.
- b) IR (infra-red spectrum) with major reflections.

Fig. 5 Morphometric versus granulometric measurements for the three facies zones. Grain size is given in μm and the morphometric data are representative of the sphericity of particles (1.0 is the ideal spherical shape “ball”). HWL = High water level.

- a) Foreshore.
- b) Backshore.
- c) Dune belt.

Fig. 6 Coal petrographic studies of the examined subbituminous coal. Photomicrographs: a to c: Incident white light, oil immersion, magnification 500 $\times$; d to f: UV light excitation, oil immersion, magnification 500 $\times$.

- a) Fragmented semi-fusinite surrounded by ulminite and a densinitic matrix.
- b) Fragments of fusinite, semifusinite, and inertodetrinite in densinitic matrix with a distinct fracture.
- c) Fusinite-cross-section of possibly root with ground tissue (cortex).
- D. Compacted textinite.
- E: Sporinite.
- F. Telalginite (Tasmanites?).

Fig. 7 Log activity vs. pH diagrams at 25°C.

- a) $\text{Log } a_{(\text{AL}^{+++})/(\text{H}^+)^3}$ vs. pH diagram to show the variation of the stability fields of minerals found in the wave-dominated unbarred marine environment. The dissolved species are used as $\text{log } a_{\text{Fe}^{++}} = -4$, $\text{log } a_{\text{Mg}^{++}} = -1$.

b) Log $a_{\text{SiO}_2(\text{aq})}$ vs. pH diagram to show the variation of the stability fields of minerals found in the wave-dominated unbarred marine environment. The dissolved species are used as $\log a_{\text{K}^+} = -3$, $\log a_{\text{SO}_4^{--}} = -3$.

Fig. 8 The periglacial subbituminous coal-sand unit from the Falkland Island as a function of the wave and tidal powers and the resultant raw materials in the various depositional environments. The marine forces along the coast are shown as a function of the environment and used to describe the effectiveness in terms of sand processing and the abundance of coal/peat.

- a) Microtidal unbarred strand plain with coal seams in the dune belt and high-purity quartz sands in the foreshore and shoreface environments.
- b) Microtidal (to mesotidal) environment with a back barrier lagoon.
- c) Mesotidal wave-dominated blind estuary.
- d) Macrotidal tide-dominated estuary.
- e) Macrotidal tidal flats.

Fig. 9 Coal-bearing coastal environments (paralic coal) from the periglacial environment of the Northern Hemisphere.

- a) The German Bight and its tidal range. The position of the two sites referred to for comparison in image 9b and 9c are shown in the white boxes (source of satellite image: Google Maps). NL = The Netherlands, D = Germany, DK= Denmark. Fasterholt is referred to in the text.
- b) Viewing the backshore and the dune belt in a microtidal environment from the Northern Hemisphere (Lodbjerg, Denmark) left over and exposed after the retreat of the ice. The subbituminous coal (c) with seat earth underneath the seam (see inset) .

c) Drill core into the meso- to microtidal Wadden Sea, Germany,

A_e = bleached eluvial topsoil horizon, B_h = illuvial horizon enriched in humic matter, B_s = illuvial horizon enriched in Fe and Al (sesquioxide) (Source of drill core: Senckenberg Institute, Wilhelmshaven, Germany) .

Fig. 10 The natural dressing plant of paralic coal seams. The vertical arrowheads reflect the upgrading of the quality of the arenaceous (silica) and argillaceous interseam sediments (clay). The pathway of the sand processing in a wave dominated environment reveals a tripartite subdivision (stage 1: reworking, stage 2: winnowing, stage 3: chemical leaching), the clay processing in a tide-dominated environment is a single-step process including only chemical leaching promoted by coal/peat (see Fig. 8c, d, e).

Fig.11 The natural dressing plant of paralic coal for kaolin a single-step leaching process in comparison to the three-step process illustrated in Fig. 10 (Dill, 2016) (see also Fig. 8c, d, e). Coal Measures in the open pits of Sachsen-Anhalt subbituminous coal mining district, shown from top to bottom.

a) Eocene to Oligocene subbituminous coal rests together with sand on top of kaolin deposits.

b) Arenaceous intertidal sediments (white = sand, brown = coal) .

c) Massive kaolin deposits.

Tables

Table 1 Sedimentary petrography of the coastal marine Quaternary sediments of the Falkland Islands and the interpretation of their depositional environment and the physical-chemical regime of formation. See also Fig. 2 for aerial distribution. n.d. = not determined

Table 2 The chemical composition of the coastal marine Quaternary sediments of the Falkland Islands in comparison to coal/peat-bearing sand units elsewhere. n.d. = not determined

a) Major elements

Falkland Islands (coastal marine/ periglacial) .

Suriname (coastal marine/ tropical humid) .

Borneo (coastal marine/ tropical humid) .

Manitoba (glacial-fluvial /periglacial) .

Fontainbleau (coastal marine/ periglacial) .

b) Trace elements of siliciclastic sediments of the coastal marine Quaternary sediments of the Falkland Islands

Table 3 Coal petrographic data.

Zonation (Fig. 2)	Environment of deposition	Heavy minerals (wt. %)	Heavy minerals	Light minerals+ phyllosilicates	Median (μm)	Sorting	Hydrographic features	Physical- chemical regime	Source	Age of formation
Zone I	Lower Foreshore (adjacent to shoreface) Periglacial cold-humid	0.05-0.1	garnet, goethite zircon, siderite (?), pyrite, rutile, hematite, amphibole, clinopyroxene, tourmaline, magnetite, ilmenite	quartz, feldspar (microcline, albite), halite, Fe-Mg chlorite, silica, illite-smectite mixed layer, illite, kaolinite, muscovite 3T, calcite, organic matter	248 Fine s. - (Medium s.)	1.148	below high water level close to the low water level, swash zone	Eh $\approx$ 0 log a (AL+++)/(H+) ³ > 7.5 log a SiO ₂ (aq) > -4 pH: 6.5 - 7	Port Stanley Beds Jurassic dyke rocks	Quaternary
Zone II	Middle-Upper Foreshore	0.1	rutile, zircon	quartz, feldspar (microcline)	223 Fine s.	1.132	below high water level. swash zone	Eh >0		Quaternary
Zone III	Backshore Periglacial cold-humid	0.2-0.3	rutile, leucoxene, garnet, spinel, monazite, zircon, tourmaline, barite, celestite (+chalcopyrite), xenotime, sphene, amphibole, clinopyroxene	quartz, feldspar (microcline), alkaline feldspar, (microcline+albite ordered), dolomite, gypsum	221 Fine s.	1.140	above the high water level, fully marine	log a (AL+++)/(H+) ³ > 7.5 log a SiO ₂ (aq) > -4 pH: 6.5 - 7 pH: 4 - 5	Port Stanley Beds Jurassic dyke rocks	Quaternary
Zone IV	Dune belt Periglacial cold-humid	0.7-2.0	garnet, rutile, amphibole, zircon, tourmaline, spinel, florencite	quartz, feldspar (microcline, albite), kaolinite, calcite, Fe halloysite, Fe-Mg chlorite, coaly matter	221 Fine s.	1.138	above the high water level, transitional marine- continental (Aeolian)	Eh >0 $\Leftrightarrow$ Eh >0	Oligocene to Early Pliocene coaly matter Primary: terrestrial to brackish marine	Quaternary + Neogene (Paleogene)
	Coal layer (reworked) Tropical-humid paralic									
Zone V	Bedrock Fluvial-marine	n.d.	garnet, zircon, monazite, rutile	Quartz, feldspar (microcline), calcite, muscovite 3T	n.d.	n.d.	n.d.	n.d.	Port Stanley Beds	Lower Carboniferous

Table 1

(wt. %)	Falkland Islands			Suriname			Borneo			Manitoba				Fontaine-bleau
	min	mean	max	min	mean	max	min	mean	max	mean	mean	mean	mean	mean
SiO ₂	96.95	97.87	98.52	96.05	97.91	99.76	96.00	97.66	99.31	75.50	86.40	89.20	89.00	99.65
TiO ₂	0.10	0.18	0.28	0.01	0.06	0.10	0.03	0.40	0.77	n.d.	n.d.	n.d.	n.d.	n.d.
Al ₂ O ₃	0.58	0.73	1.26	0.04	1.12	2.20	0.07	1.14	2.20	9.60	6.20	4.20	4.20	0.08
Fe ₂ O ₃	0.07	0.13	0.24	0.01	0.06	0.11	0.00	0.06	0.11	1.60	0.50	0.50	0.40	0.02
MnO	0.00	0.00	0.01	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MgO	0.01	0.02	0.05	0.001	0.002	0.003	n.d.	0.00	n.d.	0.80	0.40	0.30	0.20	n.d.
CaO	0.02	0.14	0.70	0.002	0.003	0.003	n.d.	0.00	n.d.	3.20	1.80	2.00	2.10	n.d.
Na ₂ O	0.02	0.03	0.08	0.003	0.012	0.020	0.00	0.11	0.21	3.10	1.60	1.10	1.20	n.d.
K ₂ O	0.17	0.24	0.35	0.004	0.047	0.090	0.00	0.05	0.09	1.90	1.10	0.90	0.70	n.d.
P ₂ O ₅	0.01	0.02	0.04	n.d.	n.d.	n.d.	n.d.	<0.01	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

Table 2a

ppm	min	mean	max
Ba	63.0	67.3	90.0
Cu	9.0	10.1	12.0
Nb	2.0	3.1	5.0
Pb	6.0	6.3	7.0
Rb	11.0	13.6	16.0
Sr	9.0	17.3	37.0
Y	7.0	7.7	9.0
Zn	4.0	4.6	6.0
Zr	61.0	183.7	404.0
Ce	7.4	10.8	14.8
I	0.5	0.9	3.1

Table 2b

Material	Rr %	N	SD	Q
Subbituminous coal	0.38	100	0.07	5

% Rr - random reflectance; N - number of measurements; S.D - standard deviation of % Rr; Q - Qualifier, refers to the reliableness of reflectance measurements derived from particle quality (size, surface quality) and statistical significance; 6 - derived from migrabitumen; 5 - very high; 4 - high; 3 - middle; 2 - poor; 1 - very poor; and 0 - indeterminable or non-derivable.

Table 3

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

„The natural dressing plant along the coast“

Tidal power max (upgrading quality of clay and increasing the quantity of peat/coal)

Wave power max (upgrading quality of sand)

Figure 8

Figure 9

Figuer 10

Figure 11