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Quantitative clay mineralogy as provenance indicator for recent muds in the southern North Sea

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ABSTRACT

The origin of recent mud deposits as well as the coastal turbidity maximum in the French-Belgian-Dutch nearshore area of the southern North Sea is still under debate in the literature. Some models favor the erosion of the Cretaceous chalk cliffs along the English Channel and subsequent NE ward directed transport, other models focus on the erosion of Eocene to earliest Oligocene, and Pleistocene to Holocene clays outcropping on the seafloor off the Belgian coast. In order to validate these hypotheses, the detailed qualitative and quantitative clay mineral composition of these sediments was used as a provenance indicator. By comparing the clay mineral composition of the mud deposits and the associated suspended particulate matter (SPM) with the composition of potential nearby and more remote sources such as the present day marine environment, estuaries and rivers, coastal erosion areas and the geological substratum, the origin of the mud deposits and the SPM could be traced. Results showed that only the clay composition of the Scheldt estuary coincides with those of the mud deposits and the coastal turbidity maximum and that all other potential sources could be excluded. Our data suggest that the clay mineral composition of the mud deposits has a similar composition since at least about 100.000 years, indicating that these deposits originate from a paleo-Scheldt river rather than from the recent river system, as the present-day Scheldt estuary is not source of fine-grained sediments. The present-day SPM in the Belgian-Dutch nearshore area originates mainly from the erosion and resuspension of the existing mud deposits situated in the Belgian nearshore. This study demonstrates the value and suitability of quantitative bulk and clay mineralogy techniques in sediment provenance studies and highlights the importance of incorporating the recent geological history in hydrodynamic studies of sedimentary basins.

1. Introduction

Sediment fluxes and budgets are required to assess the state of a marine environment and to predict changes induced by natural variability, human activities or climate change. The flux includes the transport of fine-grained suspended particulate matter (SPM) from an erosional source to a depositional sink often over long distances. Regional fine-grained sediment dynamics can be complicated by the multitude of local and remote sources, transport routes and sink. This starts with the erosion of a varying geological substratum, complex river patterns, coastal erosion and accretion, and the consecutive and temporal deposition, storage and resuspension of sediments in inter- or subtidal areas. The fine-grained sediment dynamics in the French-Belgian-Dutch nearshore area of the southern North Sea is an example of such a complicated system where the origin of a coastal turbidity maximum and of a cohesive mud deposit are still under debate as shown by the following summary of mud provenance paths suggested in literature (Fig. 1).

Fine-grained SPM entering the North Sea through the Dover Strait is suggested based on in situ and remote sensing measurements of SPM concentration, hydrodynamics and numerical models (Prandle et al., 1996; Velegrakis et al., 1999; Lafite et al., 2000; Fettweis et al., 2007a).

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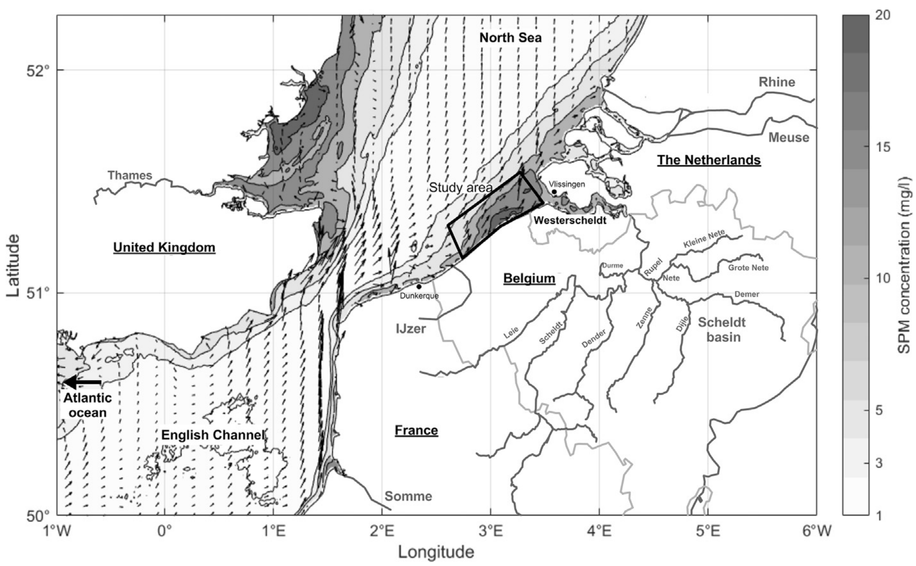

Fig. 1. Geographical overview of the southern North Sea basin showing the mud plate (black polygon) in the Belgian-Dutch nearshore area and the averaged surface SPM concentration derived from MODIS satellite and the coastal turbidity maxima of the Belgian-Dutch nearshore area indicated as greyscale variations. Arrows indicate the residual water transport in the southern North Sea and English Channel, showing a dominantly SW-NE direction (after Fettweis et al., 2007a, 2007b). The different possible source areas, English Channel, Atlantic Ocean, Scheldt river basin, Rhine & Meuse rivers are all indicated. Paleogene clays outcropping on the North Sea seafloor occur in the north to northeastern part of the mud plate.

Erosion of the Cretaceous chalk cliffs along the English Channel and the Dover Strait and the subsequent NE ward directed transport is suggested as a predominant source of fine-grained sediments in the southern Bight of the North Sea. This is based on the ruling tidal regime and wind patterns, sediment transport modeling, qualitative clay mineralogy and microfossil analysis (Eisma, 1981; Irion and Zöllmer, 1999; Gerritsen et al., 2001; Fontaine, 2004; Fettweis et al., 2007a). Fettweis and Van den Eynde (2003) suggested that the accumulation of fine-grained material in the coastal turbidity maximum results from a decrease of the residual NE ward directed SPM transport originating from the Strait of Dover. Other studies however emphasize that local erosion of Holocene to Pleistocene mud layers is most likely the main source of the cohesive mud deposits and the SPM in the turbidity maximum area (Baeteman, 1999; Beets and van der Spek, 2000; Mathys, 2009). Bastin (1974) and Le Bot et al. (2005) have suggested erosion of outcropping Eocene to earliest Oligocene clays as possible sources. Fontaine (2004) reported the presence of earliest Oligocene nanoplankton microfossils in the cohesive mud deposit implying at least a partial provenance contribution from either outcropping deposits in the southern North Sea or from their erosion in the Scheldt estuary. The contribution of the Scheldt, the Rhine-Meuse river system and the Seine is an additional potential source as these rivers had a major impact on the sediment distribution in the North Sea during the recent geological history and also presently play their role (Lacroix et al., 2004; Busschers et al., 2005; Peeters et al., 2015). The large maintenance dredging and disposal operations in the area could have an influence on the sediment dynamics as these operations relocate locally fine-grained sediments by local relocation of sediments although their regional extent remains unknown (Fettweis et al., 2009). These different mud provenance hypotheses are mainly based on an understanding of residual flow patterns in the Dover Strait and the southern North Sea and on regional geological and general sedimentological considerations. However, no systematic sediment composition analyses were carried out in support of the mud provenance.

Several studies applied qualitative and semi-quantitative clay mineral analysis as a tracer of fine-grained sediment pathways in marine, tidal and fluvial environments (Irion and Zöllmer, 1999; Sandler and Herut, 2000; Zuther et al., 2000; Kessarkar et al., 2003; Ramaswamy et al., 2007; Liu et al., 2008, 2010; Pache et al., 2008; Dou et al., 2010; Howell et al., 2014; Li et al., 2014; Schroeder et al., 2015). However, conclusions of these studies were hampered by the low resolution and limited accuracy of the applied methods. Recent methodological developments however allow for a fully quantitative and accurate analysis of clay minerals which makes them also applicable for provenance studies in fine-grained deposits (Hillier, 1999; Sakharov et al., 1999; Środoń et al., 2001; Omotoso et al., 2006; Aplin et al., 2006; Ufer et al., 2008; Hubert et al., 2009; Zeelmaekers et al., 2015; Raven and Self, 2017). The aim of the present study therefore is to apply these advanced quantitative clay mineral analysis to compare the turbidity maximum and the cohesive bottom mud sediments of the French-Belgian-Dutch nearshore area with the suggested provenance areas.

2. Background and methodology

2.1. Study area

The study area is located between the English Channel and the central North Sea (Fig. 1). The area is bounded by the Strait of Dover to the southwest and the Western Scheldt estuary to the northeast and can be considered as a link between the Atlantic Ocean and the North Sea in terms of exchanges of water, sediment and other substances. The area is a macrotidal environment, with tidal ranges up to 6 m at Dunkerque and 4.5 m at Vlissingen during spring tide. The tides are semidiurnal and tidal currents are strong, ranging between 0.5 and 1.5 m s^{-1}. The Belgian Continental Shelf (BCS) is a high-energy sedimentary environment consisting dominantly of fine- to medium-sized sand deposits structured in elongated ridges and mud to muddy sand deposits (Trentesaux et al., 1999; Le Bot et al., 2005; Verfaillie et al., 2006). The occurrence of a high turbidity zone located between about Ostend and the Western Scheldt estuary is of special interest (Fig. 1), see e.g. Fettweis and Van den Eynde (2003). The cohesive sediments on the BCS, further referred to as BCS mud plate, consist of three types with variable thicknesses (Fettweis et al., 2009, 2010): 1) fluid mud, forming the uppermost layer (cm- to dm-range) of the mud plate with a density of 1100–1200 kg/m^3, 2) weakly-consolidated, soft butter-like muds (decimeters to meters thick) with a bulk density of 1300–1500 kg/m^3 and, 3) medium-consolidated, stiffer muds sometimes intercalated with more sandy layers (0.5 m to a few meters thick) with a bulk density of 1500–1800 kg/m^3. These more consolidated muds often underlain the more weakly-consolidated and fluid muds and together form the mud plate.

2.2. Clay mineral analysis method

In the present study proven robust quantitative clay mineral analyses are used following the approach outlined by Drits et al. (1997); Sakharov et al. (1999); Środoń et al. (2001); Zeelmaekers et al. (2015). All collected samples were subjected to a systematic preparation