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Genesis of soils from Holocene tidal deposits at the North Sea coast

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ABSTRACT

The Southern North Sea coast has served as an exemplification to analyse and discuss the genesis of soils from Holocene tidal deposits. The accumulation wedge of Holocene tidal deposits at the North Sea coast is artificially embanked for the most part. In the enclosed area (hinterland) a variety of different soils developed. Disparate models attempting to explain the genesis of these soils deduce genesis of hinterland soils from recent foreland conditions, disregarding that geogenic preconditions have fundamentally changed. By consolidating and reviewing established literature we show that differences in geogenic preconditions are the initiating key for a feasible model. Describing geogenic preconditions to infer pedogenic processes, we develop a model comprising four different development pathways. High settling velocities and regular flooding, as present in the foreland, cause high inputs of mineral sediments and carbonate, moderate sulfur dynamics and thus the development of calcareous soils. Synsedimentary decalcification prevails in irregularly flooded areas due to enduring low sedimentation rates, low carbonate inputs and moderate sulfur dynamics under alternating redox states, as mainly proposed for the unobstructed landscape. High contents of soil organic matter (SOM) facilitate intensive sulfur dynamics creating potential acid sulfate soils (PASS), which become extreme acid upon oxidation (actual acid sulfate soils (AASS)). A great gradient in depositional conditions, occurring at unobstructed plain coasts, enables the deposition of deflocculated fine-grained sediments which promotes the formation of very compact soils with low water conductivities. Although this proposed model is based mainly on conditions known from the German North Sea coast, it is shown that shaping geogenic and pedogenic processes are applicable to other humid coastal regions around the world.

1. Introduction

The 400,000 km worldwide coastline (Gierloff-Emden, 1980) forms the transition zone between oceans and continents. At steep coasts this transition is narrow, but shallow coasts yield broad tidal-influenced transition zones and therefore enable the deposition of tidal sediments and the development of wide tidal flats and tidal marshes, namely mangroves in the tropics. Tidal deposits settle under marine conditions as well as under brackish and freshwater conditions in tidal-influenced estuaries and upstream. The main driver generating these deposits is the post-glacial sea level rise (Allen, 2000). Other fundamental requirements for the development and maintenance of tidal flats, tidal marshes and mangroves are topographically/geomorphologically protected areas facilitating sedimentation and sediment sources (Long and Mason, 1983), as well as a large tidal range. The type and amount of sediment sources, climatic conditions and the effectiveness of oceanic processes (tides, waves, storms, geometry of the basin) generate different kinds of deposits (Martini, 2014). When marsh accretion is correlated with plant biomass production, which supplies soil organic matter (SOM), organo-rich deposits arise (typically occurring in North America) (DeLaune and Pezeshki, 2003; Kirwan and Megonigal, 2013), whereas accretion in predominant minerogenic marshes is spatially differentiated by a levee-depression topography which is triggered by creek system development (Allen, 2000; de Groot et al., 2011b). Sediment distribution patterns differ globally and on local and regional scales as well as on temporal scales. Therefore subsequent pedogenesis can only be explained with knowledge of landscape development during the Holocene (Dent and Pons, 1995).

Soil formation and thereby transformation of tidal sediments start when sediments achieve elevations above the mean high water line (MHWL) or with colonization by higher plants and further continues with increasing elevation relative to MHWL. However, pedogenesis is interrupted and set back by irregular flooding events initiating recurrent geogenesis. This alternation of geogenic and pedogenic processes is defined as geo-pedogenesis (Brümmer, 1968). Human interference in river catchments and large-scale marsh embankment has disrupted these natural regimes all over the world (Kirwan and Megonigal, 2013).

In this study we mainly focus on genesis of soils from Holocene tidal

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deposits at the German North Sea to outline general genetic processes in these sediments. Humans started diking in this region in the 11th century. Since diking was completed in the 13th century (Behre, 2004) a continuous dike system has separated areas of tidal deposits with tidal influence (foreland) from those without tidal influence (hinterland), the latter exclusively governed by pedogenesis. As dike constructions are vulnerable, several catastrophic storm surges, which were a consequence of the reduced flood-water storage capacity, created new bays at medieval times. Some of these bays still exist today (Dollart Bay and Jade Bay), others silted up, supported mostly by man-made land reclamation (Behre, 2004). Hinterland soils from tidal deposits show a large variation in properties. This is evident by the assignment to different reference soil groups as well as by the attribution of different principal and supplementary qualifiers according to IUSS Working Group WRB (2014). Most widespread are *Gleysols*, which exhibit *calcaric*, *eutric*, *dystric*, *sulfidic* and/or *thionic* properties (Hartwich et al., 2007). Some of these *Gleysols* were classified as *Fluvisols* according to IUSS working group WRB (2006). Scattered soils with *stagnic* properties (*Stagnosols* or *Planosols*) also occur. *Histosols* mainly developed in depressions and in the transition belt between Holocene tidal deposits and the Pleistocene moraine. Some authors also describe soils with *Solonetz*-like properties (Müller-Ahlten, 1994a; Müller, 1954; Veenenbos, 1955). According to the German Soil Taxonomy seven of 56 soil types are assigned to soils developed from tidally deposited parent materials (Ad-hoc-AG Boden, 2005), which further illustrates the diversity of these soils.

Different models have been established since the 1940s, which attempt to explain the diversity of soils built up by tidal deposits. The first model was a temporal-genetic one, which explained different properties of soils from tidal deposits based on their maturing time (Laatsch, 1944; Mückenhausen, 1957; Scheffer and Schachtschabel, 1956). This model was rejected as no general correlation was found between soil properties and maturing time and was replaced by a model based on causal determination of sedimentation and soil properties (Edelman, 1950; Veenenbos, 1953; Veenenbos and Schuylenborgh, 1951), which was further elaborated by Müller (1954). In Müller's model the cation composition of the water column during sedimentation is of essential importance for the properties of the developing soils, separating them mainly by the Ca/Mg ratio and K/Na ratio of exchangeable cations into marine, brackish and freshwater deposits. In addition soils containing large amounts of SOM were merged into a separate group. Later a morpho-genetic model was introduced by Brümmer (1968) in which sulfur dynamics are of major importance. In a genetic sequence salt-affected, calcareous, non-calcareous and clay translocated soils were separated and a SOM-rich variant was created. Thereafter the validity of Müller's and Brümmer's models was questioned. Brümmer's model became increasingly accepted, likely as a result of findings in the 1980s (Giani, 1983).

A principal shortcoming of all these models is that they consider genesis of soils from tidal deposits as a unidirectional process. For this they mainly refer to recent foreland conditions to explain the initial stage of pedogenesis for older soils in the hinterland. However geogenic preconditions have naturally changed during the Holocene (Hoselmann and Streif, 2004) and have been fundamentally altered by the development of dikes (Dellwig et al., 2000; Flemming and Nyandwi, 1994). Consequently genesis of hinterland soils cannot be deduced simply from recent foreland conditions. Therefore, a literature review was conducted with regard to geogenic preconditions during Holocene landscape development at the German North Sea and four main initial stages were distinguished for further development from which a genetic model featuring a four-pathway structure evolved. The main purpose of this study is to outline how geogenic preconditions affect general geopedogenic processes proceeding synsedimentary at the initial stage of development and subsequent pedogenic processes, as well as to illustrate the transferability of the different pathways to other coastal areas worldwide.

2. Geogenic preconditions

Natural, temperate tidal zones are characterized by a complex network of creeks and channels (Allen, 2000; Gerrard, 1981). Tidal water loaded with suspended sediments enters a marsh via the marsh edge or via the creek system depending on inundation height and development stage of the creek network (Temmerman et al., 2005). A progressive settling of sediments leads to the highest sedimentation potentials close to tidal creeks and the marsh edge (de Groot et al., 2011b). Consequently, deposits in close proximity to these places are mainly built up by minerogenic sediments, while those occurring at greater distances are composed of greater proportions of organic matter derived from the marsh vegetation itself (Rabenhorst and Needelman, 2016). Rivers and streams additionally deliver terrestrial mineral particles and terrestrial sedimentary organic matter, which are mainly trapped in the upper part of estuaries (Caliani et al., 1997; Sondi et al., 2008). In general, thickness and the mean settling velocity characteristics of the mineral deposits decline with increasing distance to creeks or the marsh edge (Allen, 2000); resulting in a progressively landward fining of sediments. However, this is not generally reflected by the grain size of the deposits, because mineral particles < 8 μm form flocs and aggregates which have higher settling velocities than their constituent particles (Chang et al., 2007; Chang et al., 2006). Different cation compositions of the tidal water impact the flocculation of clay (Gebhardt et al., 1965; Schroeder and Brümmer, 1969), causing the deposition of deflocculated fine grained sediments under brackish conditions (Veenenbos, 1955). In addition to distance to creeks and marsh edge, topographic and bathymetric elevation control the sedimentation rate, because areas of lower elevation are submerged more frequently and have a greater potential for receiving sediments than those of higher elevations (Kirwan and Megonigal, 2013; Rabenhorst and Needelman, 2016).

Similar geogenic conditions controlled sedimentation at the German North Sea coast before diking (Fig. 1). Holocene tidal deposits cover a zone of around 8100 km^2 (calculated from Hartwich et al. (2007)) and reach a thickness of 20–25 m (Streif, 2004). From about 8500 BP, when sea-level rise initiated the formation of the coastal accumulation wedge (Hoselmann and Streif, 2004), till the 11th century, when the practice of diking began, a large gradient in depositional conditions formed deposits of varying contents of quartz, clay, carbonates, the latter originating from biogenic sources (crushed shells, Foraminifera, Ostracoda, spines of Echinodermata etc.) (Verhoeven, 1962), organic matter (Dellwig, 1999) and detrital terrigenous minerals (Caliani et al., 1997). Hoselmann and Streif (2004) roughly estimated an average sedimentation rate of 0.99 cm yr^{-1} for the time period 9000–6000 cal BP and of 0.16 cm yr^{-1} for the time period 3500–1000 cal BP. Coarse- and medium-grained sand deposits formed at the seaward edge and along big creeks. More landward, several kilometre wide vast areas solely received fine grained sediments, which is reflected by the term ‘clay district’ used for this area (Behre, 2004). Additionally, areas covered with Phragmites swamps developed (Bantelmann, 1984) (Fig. 1). Under transient high energy conditions sand was deposited in areas normally receiving finer grained sediments (de Groot et al., 2011a), causing an internal stratification by sand laminae (also called storm surge layers). However, a rapid decrease in transport energy of the water, when entering the vegetated plain, inhibited an extent of these sand laminae far inland. Where Holocene deposits wedge out against the Pleistocene moraine thick peat bogs formed (Streif, 2004). Sea water and marine sediment incursion in these areas of peat formation was widespread in the open landscape (Dellwig et al., 2001).

Most of the depositional environments of the unobstructed landscape have no analogues in the present embanked landscape, because tidal influence is restricted to a narrow belt in the foreland and irregular incursion of sea water and tidal sediments into the vast, plain areas of the hinterland and into areas of peat formation is inhibited, as well as Phragmites swamp formation. Despite these inhibitions the grain size