Subaqueous Soils: An Overview

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Abstract

Subaqueous soils are fundamentally different from their subaerial counterparts. Submerged soils are a fairly new field of study, only recently defined and classified, with their own unique taxonomy. Pedogenic processes must be evident in a subaqueous soil. Subaqueous soils are acted upon by soil forming factors, however, these may be different than the commonly accepted subaerial soil forming factors. Submerged soils also have distinctive chemical and physical characteristics, including an inadequately explored capacity for carbon sequestration. With rising sea levels, the study of subaqueous soils is vital to the future of pedology.

Introduction

What is a soil? The definition of soil is ever-evolving. Over the past few decades, the official boundary between soil and sediment has grown murkier as new classifications have been developed to describe the submerged soils that exist at the land-water interface. A subaqueous soil is uniquely different from nearby subaerial soils or deeper water sediments. These soils are not yet fully understood and new research and new ideas are still shedding light upon their distinctive characteristics. Recognizing a soil can help researchers to frame their thinking when working in marine and estuarine environments.

Definition

The official USDA definition of soil used by many American soil scientists was altered to include subaqueous soils in 1998 (Demas and Rabenhorst, 1999). *Keys to Soil Taxonomy* (Soil Survey Staff, 2014) now defines a soil as:

> Soil in this text is a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment (Soil Survey Staff, 1999). This definition is expanded from the previous version of *Soil Taxonomy* (Soil Survey Staff, 1975) to include soils in areas of Antarctica where pedogenesis occurs but where the climate is too harsh to support the higher plant forms.
>
> The upper limit of soil is the boundary between soil and either air, shallow water, live plants, or plant materials that have not begun to decompose. Areas are not considered to have soil if the surface is permanently covered by water too deep (typically more than about 2.5 m) for the growth of rooted plants. The horizontal boundaries of soil are areas where the soil grades to deep water, barren areas, rock, or ice. In some places the separation between soil and nonsoil is so gradual that clear distinctions cannot be made.

A subaqueous soil has all the same diagnostic characteristics as a subaerial soil and is submerged year-round under waters up to 2.5m deep.

Extent

The United States has more than 95,000 miles of shoreline (NOAA). Florida alone accounts for more than 8,000 (8.8%) of those shoreline miles, about 5,000 miles on the Gulf coast and 3,000 miles on the Atlantic coast (NOAA). Florida also has approximately 26,000 miles of river (National Wild and Scenic Rivers System). While there has not yet been a large-scale mapping project for subaqueous soils, Florida, with its abundance of water, is involved in subaqueous soil research and identification, along with Rhode Island, Maine, Delaware, Texas and other states with extensive coastlines (NRCS). A joint project between the University of Florida Whitney Marine Laboratory and the St John's River Water Management District was initiated to create a subaqueous soil survey of the Indian River Lagoon, following an algal bloom in 2011 that impacted the estuary (NRCS). The project was successful in mapping approximately 90,000 acres, primarily seagrass beds (NRCS).

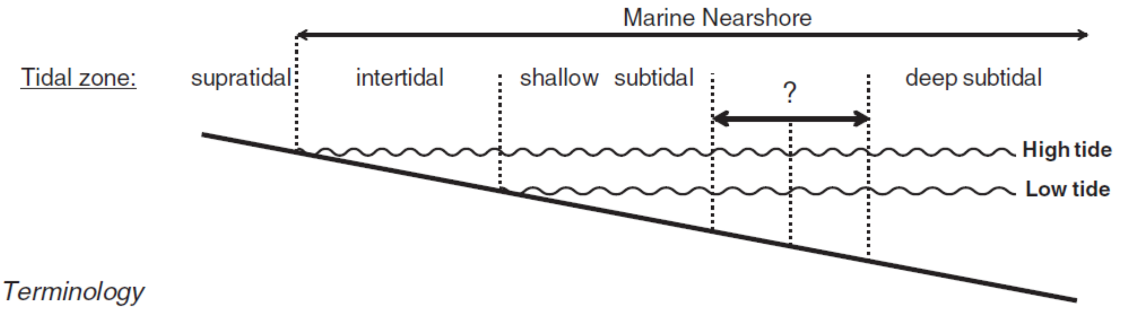
Subaqueous Soils vs Sediments

The distinction between sediment and soil differs between scientific disciplines (Figure 1) (Kristensen and Rabenhorst, 2015). As such, it is important for researchers to clearly distinguish between subaqueous soil and sediment to avoid confusion.

The word sediment comes from "the Latin word *sedimentum* (year 1540-50), which means act of settling" (Kristensen and Rabenhorst, 2015). Aquatic sediments consist primarily of solid particle deposition, both allochthonous and autochthonous, organic and inorganic

(Kristensen and Rabenhorst, 2015). Near-shore sediments tend to be terrigenous and transported by streams or rivers, while deeper ocean sediments are more likely to be to be comprised of shells and dead microorganisms (Kristensen and Rabenhorst, 2015). Marine sediments are constantly saturated and therefore anoxic below a thin surface oxic layer (Kristensen and Rabenhorst, 2015).

Figure 1. Sediments (as defined by Marine Scientists) vs Subaqueous Soils (as defined by Pedologists)



Terminology

Marine Scientists	soil	sediment		
Pedologists	soil	soil (since 1970s)	soil (since 1999)	sediment

(Kristensen and Rabenhorst, 2015)

The word soil comes from "Middle English or Anglo-Norman French (year 1300-50) and means 'a piece of ground derived from Latin '*solium'* (meaning 'seat') by association with '*solum'* (meaning 'ground')" (Kristensen and Rabenhorst, 2015). In order to be considered a soil, horizon differentiation must occur as the result of pedogenic processes (Demas and Rabenhorst, 1999). These processes can be summarized as additions, removals, transfers or translocations, and transformations (Demas and Rabenhorst, 1999; Kristensen and Rabenhorst, 2015). The current definition of a soil requires recognizable horizons or the ability to support rooted plants (Soil Survey Staff, 2014). Therefore, plant life is not necessary in the presence of clear pedogenic horizons and – in rare cases – a soil may be identified if rooted plants are present even in the absence of horizons (Kristensen and Rabenhorst, 2015).

Pedogenesis

Subaqueous soils demonstrate pedogenic processes (Table 1) such as additions, removals, transfers, and transformations (Demas and Rabenhorst, 1999). Pedogenic additions include mineral material such as sediment deposits and shell fragments and organic material such as vegetative debris (Demas and Rabenhorst, 1999). Pedogenic removals include microbial decomposition and erosion due to storms, waves, and currents (Demas and Rabenhorst, 1999). Leaching and seepage – removals common in subaerial soils – are not significant in a permanently submerged soil system (Demas and Rabenhorst, 1999). Pedogenic transfers include diffusion via dissolved oxygen and bioturbation via benthic organisms (Demas and Rabenhorst, 1999). Eluviation, although a common subaerial pedogenic transfer process, is not applicable in a subaqueous environment (Demas and Rabenhorst, 1999). Pedogenic transformations include sulfidization and the conversion of organic matter to different humic substances (Demas and Rabenhorst, 1999).

Table 1. Pedogenic Processes

Generalized Process	Sediment Diagenetic Processes
Additions	Input (sedimentation) of minerals (terrigenous, biogenic, authigenic) Input (sedimentation) of organic debris (marine, terrestrial)
Losses	Erosion Organic matter decomposition
Transfers (or Translocations)	Diffusion Porewater advection Bioturbation
Transformation	Mineralization (aerobic and anaerobic) E-acceptor zonation Nitrification and denitrification Sulfur/metal oxidation and reduction Authigenic mineral formation

(Kristensen and Rabenhorst, 2015)

Subaqueous Soils vs Subaerial Soils

Although subaqueous and subaerial soils share diagnostic properties, there are unique taxonomic, chemical, and physical distinctions between the two.

Taxonomy

Subaqueous soils can be classified into two unique suborders: Wassents and Wassists (Ferronato et al., 2015). Wassents are “Entisols that have a positive water potential at the soil surface for more than 21 hours of each day in all years" (Soil Survey Staff, 2014) while Wassists are "Histosols that have a positive water potential at the soil surface for more than 21 hours of each day in all years" (Soil Survey Staff, 2014).

Wassents are divided into the following great groups: Frassiwassents, Psammowassents, Sulfiwassents, Hydrowassents, Fluviwassents, and Haplowassents (Soil Survey Staff, 2014). Frassiwassents are "Wassents that have, in all horizons within 100 cm of the mineral soil surface, an electrical conductivity of less than 0.2 dS/m in a 1:5 (soil:water), by volume, supernatant (not extract)" (Soil Survey Staff, 2014). Psammowassents are "[o]ther Wassents that have less than 35 percent (by volume) rock fragments and a texture class of loamy fine sand or coarser in all layers within the particle-size control section" (Soil Survey Staff, 2014). Sulfiwassents are "[o]ther Wassents that have a horizon or horizons with a combined thickness of at least 15 cm within 50 cm of the mineral soil surface that contain sulfidic materials" (Soil Survey Staff, 2014). Hydrowassents are "[o]ther Wassents that have, in all horizons at a depth between 20 and 50 cm below the mineral soil surface, both an *n* value of more than 0.7 and 8 percent or more of clay in the fine-earth fraction" (Soil Survey Staff, 2014). Fluviwassents are "[o]ther Wassents that have a total thickness of less than 50 cm of human-transported material in the surface horizons and *one or both* of the following: 1. At a depth of 12.5 cm below the mineral soil surface, an organic-carbon content (Holocene age) of 0.2 percent or more and no densic, lithic, or paralithic contact within that depth; *or* 2. An irregular decrease in organic-carbon (Holocene age) between a depth of 25 cm and either a depth of 125 cm below the mineral soil surface or a densic, lithic, or paralithic contact, whichever is shallower" (Soil Survey Staff, 2014). Haplowassents are "[o]ther Wassents" (Soil Survey Staff, 2014).

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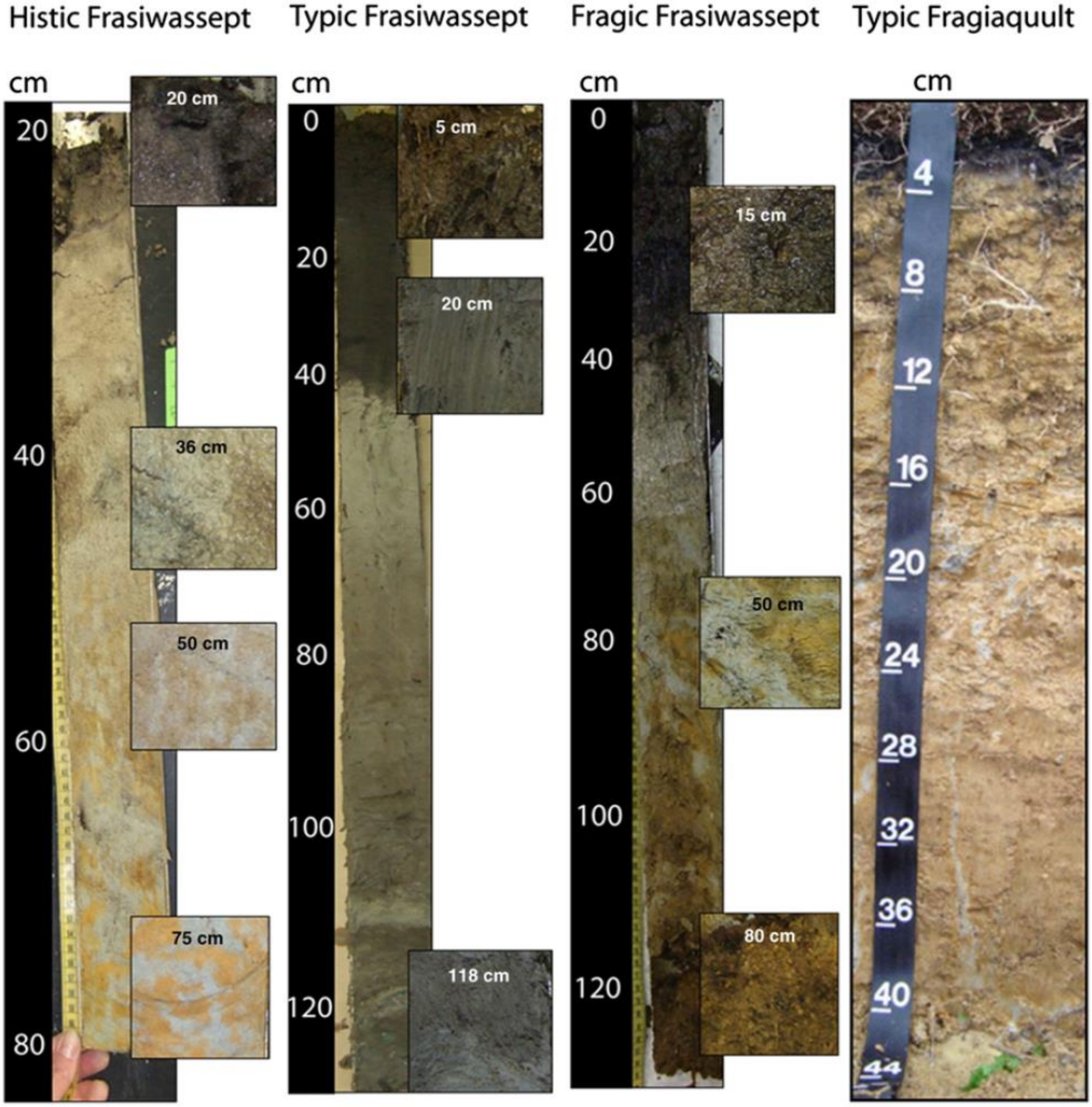
Although not an officially recognized classification, E. Erich and P.J. Drohan have proposed the Wassept (Figure 2) as an additional subaqueous soil suborder (Erich and Drohan, 2012).

Classifying subaqueous soils gives researchers a clear understanding of the composition of the submerged landscape – be it mineral or organic. Soil classification also allows for soil profiles, indicating horizon thickness, clay content, discontinuities, and more.

Figure 2. Proposed Wassept vs Subaerial Aquult



(Erich and Drohan, 2012)

Soil Forming Factors

Hans Jenny's state factor equation for soil formation is S = *f*(C, O, R, P, T) where C is climate, O is organisms, R is relief, P is parent material, and T is time (Demas and Rabenhorst, 2001). D.W. Folger developed a similar equation for sediment genesis in the early 1970s: Se = *f*(G, H, B) where G is geology, H is hydrologic condition, and B is bathymetry (Demas and Rabenhorst, 2001). In 2001 G.P. Demas and M.C. Rabenhorst proposed a new equation for the formation of subaqueous soils: Ss = *f*(C, O, B, F, P, T, W, E) where "Ss is subaqueous soil, C is climatic temperature regime, O is organisms, B is bathymetry, F is flow regime, P is parent material, T is time, W is water column attributes, and E is catastrophic events" (Demas and Rabenhorst, 2001).

This proposed equation takes into account not only well-understood subaerial soil forming factors but also allows for aquatic conditions that uniquely affect subaqueous soils. Unlike in Jenny's traditional subaerial soil model, the proposed equation does not include precipitation in C (climate/climatic temperature regime), instead focusing on the impact of temperature on aspects such as rate of organic matter decomposition (Demas and Rabenhorst, 2011). O (organisms) contribute to "the development of light colored, relatively thick surface horizons" via "benthic burrows with oxygenated water" but are not accounted for in Folger's sediment model (Demas and Rabenhorst, 2011). Jenny's R (relief) is replaced by B (bathymetry) and F (flow regime) because the catena concept of interlocking soils cannot be applied in an underwater environment (Demas and Rabenhorst, 2011). Instead, bathymetry and flow regime together shape the underwater landscape (Demas and Rabenhorst, 2011). P (parent material) and T (time) are relatively unchanged from Jenny's subaerial equation – source material and “time available for the expression of subaqueous soil attributes” both have obvious effects on subaqueous soil formation (Demas and Rabenhorst, 2011). W (water column attributes) accounts for different dissolved components such as sodium, sulfate, or oxygen that can impact subaqueous soil formation and characteristics. E (catastrophic events) allows for major storms or other unforeseen circumstances.

Chemistry

Subaqueous soils are important carbon sinks, comparable to their terrestrial counterparts (Table 2) (Millar et al, 2014). Carbon accumulates in subaqueous soils not only due to low rates of organic matter decomposition but also due to the carbon stored in shell fragments (Millar et al, 2014). Shells in the fine-earth fraction of a subaqueous soil can account for 8% to 44% of the total carbon, a considerable amount that is not seen in most subaerial soils (Millar et al. 2014).

Table 2. Soil Organic Carbon in Subaqueous Soils vs Subaerial and Wetland Soils

Drainage Class	Soil Classification	Mean SOC (Mg/ha^{-1})
Excessively Drained Uplands	Typic Udipsamments	110
Well Drained Uplands	Typic Dystrudepts	136
Poorly Drained Palustrine Wetlands	Aeric Endoaquepts	187
Poorly and Very Poorly Drained Riparian Wetlands	Aeric Endoaquepts	246
Very Poorly Drained Palustrine Wetlands	Typic Haplosaprists	586
Subaqueous	Fluventic Psammowassents	47
Subaqueous	Sulfic Psammowassents	57
Subaqueous	Typic Fluviwassents	109
Subaqueous	Haplic Sulfiwassents	123
Subaqueous	Typic Sulfiwassents	141
Subaqueous	Fluventic Sulfiwassents	196
Subaqueous	Thapto-Histic Sulfiwassents	494

(Millar et al, 2014)

Research indicates that subaqueous soils, on average, are warmer than comparable subaerial soils (Salisbury and Stolt, 2011). Likewise, subaqueous soil temperature varies with water temperature (Table 3), which can be used as a predictor for soil temperature (Salisbury and Stolt, 2011).

Table 3. Average Subaqueous Soil Temperatures and Water Temperatures at Coded Sites

Site (Logger Depth)	Average Soil Temperatures (®C)			
	Annual	Summer	Winter	Summer-Winter
NWF 25 cm	12.3	22.3	3.5	18.8
NWF 50 cm	12.3	20.5	4.9	15.6
NLB1 25 cm	12.5	19.8	6.3	13.5
NLB2 50 cm	12.6	17.9	7.6	10.3
QWF 25 cm	12.1	21.6	3.5	18.3
QSMB 25 cm	12.1	20.7	4.7	16.0
QLB 25 cm	10.8	16.9	5.6	11.4
Tidal Marsh 40 cm	8.7	16.8	4.5	12.3

Site (Logger Depth)	Average Water Temperatures (®C)			
	Annual	Summer	Winter	Summer-Winter
NWF	11.5	23.0	2.2	19.7
NLB1	12.0	22.3	2.8	19.5
NLB2	12.0	20.5	4.4	16.1
QWF	12.1	22.0	3.5	18.5
QSMB	12.4	21.8	4.3	17.5
QLB	11.2	19.5	4.2	15.3

(Salisbury and Stolt, 2011)

Studies into other properties of subaqueous soils have revealed gaps in current knowledge. There is not an obvious relationship between geomorphology, subaqueous soil texture, and soil organic carbon, as would be expected based on extrapolation from subaerial soils (Serrano et al., 2016).

Discussion and Conclusion

A better understanding of subaqueous soils allows for more accurate soil mapping and carbon budgeting (Millar et al., 2014). Coastal ecosystems and seagrass beds have blue carbon sequestration potential which needs to be accounted for in climate change models and predictions (Armitage and Fourqurean, 2016). Knowledge of subaqueous soils is extremely valuable to marine and estuarine conservation and restoration efforts (Brady and Weil, 2008), to understanding the growth and nutrition of seagrasses and other submerged aquatic vegetation (Serrano et al., 2016), and to successful aquaculture (Still and Stolt, 2014).

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