Subaqueous Soils: Pedogenesis in a Submersed Environment

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ABSTRACT

Proposals for the inclusion of permanently submersed materials in soil taxonomic systems have periodically been put forth since some time in the mid 1800s. The proposals were largely conceptual in nature, relying more on subjective reasoning rather than analytical and field data. Advances in computer and global positioning technology, and the continuing development of the discipline of pedology provided the opportunity to examine shallow water estuarine sediments within a pedological framework. Morphological and analytical data from 85 1.5- to 2.0-m profiles from Sinepuxent Bay, Maryland, indicate that the four pedogenic processes of additions, losses, transformations, and transfers outlined in the generalized theory of soil genesis are active in a subaqueous environment. The evidence of pedogenic processes includes the addition of biogenic calcium carbonate (shells), organic fragments, and organic matter; the loss of organic matter and surficial material; the transfer of oxygen through diffusion and bioturbation processes; and the transformation of humic substances and sulfur (sulfidization). The change in the concept of estuarine substrates from sediment to soil has significant ramifications for pedologists, ecologists, estuarine researchers, and government agencies involved in soil resource inventory and estuarine restoration programs. Application of these concepts could help further our understanding of the relationships between subaqueous soil distribution and submersed aquatic vegetation (SAV); clam, scallop, and oyster habitat; and dredge sites with potential acid-sulfate weathering. This work resulted in a change to the definition of soil in *Soil Taxonomy* to include subaqueous soils that are capable of or presently support rooted SAV.

Although some of the relationships between sediment characteristics and estuarine living resources have been well documented (Sanders, 1958; Rhoads, 1974; Barko et al., 1991), estuarine restoration efforts have been hindered by the lack of an adequate understanding of sediment distribution (Chesapeake Bay Program, 1991). The present methods for sampling and delineating sediment attributes evolved largely within the geologic community and have remained relatively unchanged for more than 50 yr. For example, maps portraying sediment characteristics are typically presented at scales of 1:100 000 or smaller and each attribute is cartographically displayed on an individual basis by means of isobar contours or delineations (Louderback, 1939; Folger, 1972; Kerhin, 1980). In addition, surficial sampling commonly combines layers with major differences in chemical and physical properties, there is no sediment classification scheme, and sampling is performed by means of widely space grids (Louderback, 1939; Ryan, 1953; Wells et al., 1994). Thus, the relationship between the distribution of benthic flora and fauna and sediment parameters is difficult to determine. To apply a new approach, a pedological approach, it is necessary to demonstrate that shallow water sediments can be described by a pedological paradigm.

Since the inception of pedological research, debate concerning the inclusion of subaqueous materials in soil taxonomic systems has arisen periodically (v.Post, 1862; Kubiena, 1948; Arbeitskries Bodensystematik, 1985). The question at the center of the debate seems to be related to the concepts of the "upper limit" of soil and the scientific definition of soil. Many pedologists believe that the upper limit of soil must be the atmosphere (Nikiforoff, 1958; Simonson, 1959; Foth, 1978), while in other cases the boundary is considered to include shallow water (Kubiena, 1953; Goldschmidt, 1958; Muckenhausen, 1965; Ponnamperuma, 1972; Soil Survey Division Staff, 1993; Demas 1993; Demas et al., 1996). A more important aspect of the debate concerns the definition of soil. The two main components of the pedologic definition of soil contained in *Soil Taxonomy* are that soils must be "capable of or presently supporting plants out-of-doors" (Soil Survey Staff, 1975) and/or they must show evidence of horizon differentiation due to pedogenic processes (Soil Survey Division Staff, draft, 1996). Although the role of soil as a medium for plant growth is both culturally and scientifically important, the emphasis on pedogenic processes is significant to understanding soil-landscape models, which are based on the relationship between landforms and the expression of soil attributes (Hudson, 1992). Therefore, if the four components of the generalized theory of soil genesis (Simonson, 1959) are actively functioning in a permanently submersed environment, then it might be possible to develop a predictive model to explain soil distribution across the subaqueous landscape. The development of a predictive subaqueous soil-landscape model and the use of *Soil Taxonomy* would result in a substantial increase in sampling efficiency, map accuracy, and utility of estuarine resource inventories in comparison to those presently available.

The objective of this study was therefore to evaluate the evidence of pedogenic processes in shallow water estuarine sediments to determine whether sediments would be better understood as subaqueous soils.

MATERIALS AND METHODS

Site Description

The area examined (Fig. 1) is a portion of Sinepuxent Bay, Maryland, a shallow (water depth <5 m) coastal estuary. It is bounded to the east by Assateague Island and to the west by the Worcester County mainland. Atlantic Ocean water enters and exits the site from the north through the Ocean

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Abbreviations: OC, organic carbon; SAV, submersed aquatic vegetation; TSS, total suspended solids.

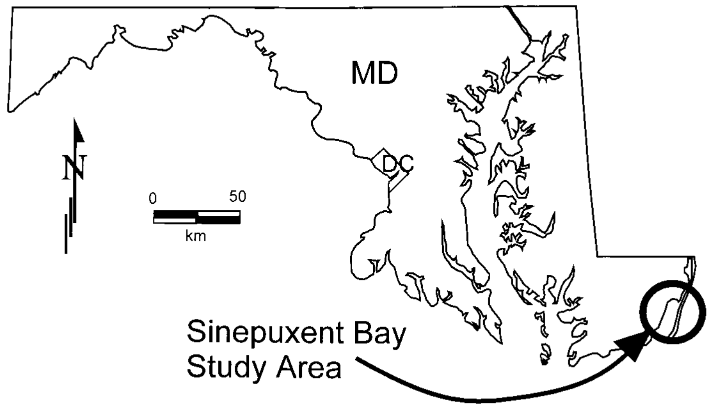

Fig. 1. Location map of Sinepuxent Bay, Maryland, study area.

City Inlet and from the south through the Chincoteague Inlet. Tidal range in the bay is small, ranging from 0.5 to 0.75 m (U.S. Dep. of Interior, National Park Service, Assateague Island, unpublished data).

Field Procedures

Through the use of a Rockwell PLGR+ Global Positioning System unit (Rockwell International, Milwaukee, WI), a Raytheon DE-719cm marine research fathometer (Raytheon Company, MA), and Geolink external device system software (GeoResearch, Inc., Billings, MT), a detailed bathymetric map of the 1300-ha site based on over 23 000 geo-referenced depth data points was generated. By means of pedological terrain analysis techniques (Soil Survey Staff, 1993), 12 individual landscape units were identified on the basis of bathymetry, slope, landscape configuration, and geomorphic setting. Similar landscape units were grouped into representative subaqueous landform types. Within Sinepuxent Bay seven major landforms were identified by both descriptive nomenclature and commonly used estuarine terminology (Demas and Rabenhorst, 1998).

To evaluate whether pedogenic processes are active in permanently submersed estuarine substrates, sediment profiles were described within each landscape unit, and along transects across landforms. A total of 85 sediment profile descriptions were recorded, of which 75 were performed in the field, nine were done in the laboratory after extrusion of vibracore samples, and one was described on the basis of vibracore data reported by Wells et al. (1996). The locations of the 75 field profile descriptions and the locations of the 10 vibracore sampling sites (A-Rep through J-Rep, and CB-1) in Sinepuxent Bay are shown in Fig. 2. Morphological descriptions of all profiles followed the procedures and notations outlined in the *Soil Survey Manual* (Soil Survey Staff, 1993).

Sampling and Laboratory Procedures

Pedons representative of each landform were sampled to a depth of at least 1.5 m with a vibracoring device and a 7.6-cm (outside diameter) aluminum pipe. After extraction of each core the end of the pipe was filled with ambient bay water and sealed. The cores were then transported a short distance to Horn Point Environmental Laboratory where they were stored frozen until they were taken to the University of Maryland at College Park for analysis. The frozen cores were extruded and profile descriptions were recorded. The cores were sampled by horizon, sparged with nitrogen, sealed, and kept frozen until sulfide analyses were completed.

Acid-volatile sulfides and chromium reducible sulfides (mainly pyrite) were determined by the procedure of Cornwell and Morse (1987). Samples were handled under a nitrogen atmosphere prior to analysis. Once sulfide analyses were completed, samples were air dried, crushed, and sieved for other analyses. Particle size analyses were performed by a modified pipette method (Kilmer and Alexander, 1949), where prior to analysis, samples were dialyzed to remove salts. Organic carbon content was determined by the combustion procedure of Rabenhorst (1988). Total carbon was determined by combustion at 1050°C with a Leco CNH Analyzer (LECO Corp., St. Joseph, MI) equipped with an infra-red detector (Campbell, 1992). Calcium carbonate-carbon content was calculated by difference between total carbon and organic carbon. Total suspended solids in the water column were measured by a modified gravimetric method (Banse et al., 1963), wherein samples collected in the field were filtered immediately. Radiocarbon analysis was performed by Beta Analytic in Miami, FL, using a standard radiometric analysis with acid wash pretreatment. A Libby ^{14}C half-life of 5568 yr was used for age calculations, and years before present refers to years before 1950 AD.

RESULTS AND DISCUSSION

Sediment or Soil?

Although there have been proposals that shallow water sediments could be considered subaqueous soils, the prevailing view in the ecologic, geologic, and pedologic communities is that shallow water sediments are nonsoil. To conclude that estuarine sediments are actually soils; pedogenic processes must be actively functioning in support of horizon differentiation. Although differing layers within a sediment column can often be identified, the critical question is whether these layers are the result of the actions of the four major processes leading to soil horizon differentiation. These processes were described in the generalized theory of soil genesis as additions, removals, transfers, and transformations (Simonson, 1959).

Pedogenic Additions

Additions to sediments documented in Sinepuxent Bay include those of mineral and biogenic origin. The addition of mineral material is particularly evident in sediment profile F-Rep (Table 1) where the surface layer of an organic paleosol has been buried to a depth

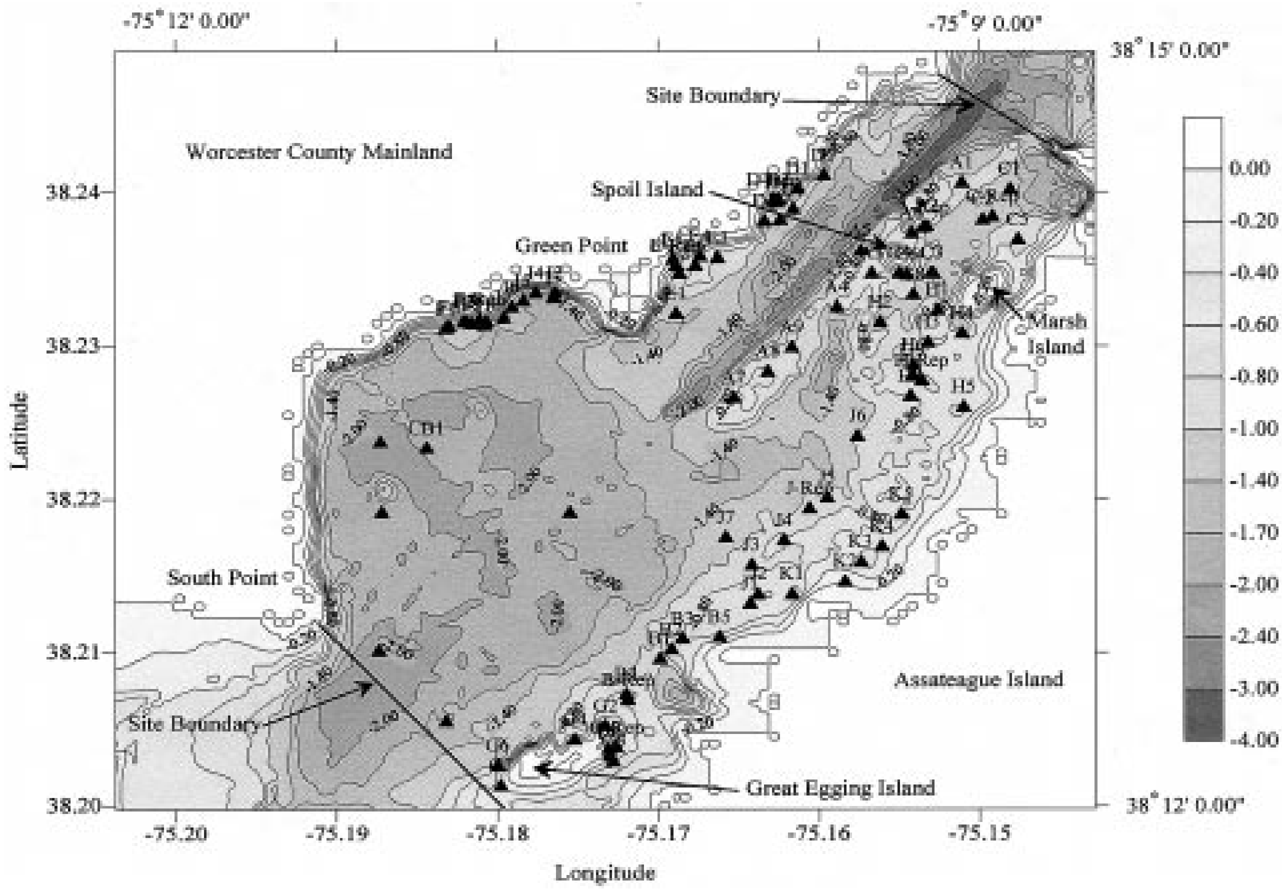

Fig. 2. Location map of pedons and vibracore sampling sites in Sinepuxent Bay, Maryland, (depth in meters below mean sea level).

of 92 cm. A buried organic layer at a depth of 150 cm in the sediment column (Oeb horizon) from a similar profile approximately 80 m northeast of the F-Rep core site, yielded a wood sample which was dated radiometrically at 1430 ± 60 yr BP (before 1950). Including the depth of the water at this location (100 cm), the elevation of the sampled wood fragment is approximately 2500 mm below mean sea level. The average rate of addition can be calculated to be approximately 1.8 mm/yr (2500 mm/1430 yr), which is within range of long term sea-level rise estimates for this region (Hicks et al., 1983; Griffin and Rabenhorst, 1989). In this case, the deposition of mineral material can be considered more of a geologic sedimentary process rather than a true pedogenic addition.

As a result of the addition of mineral material, Sinepuxent Bay sediments, in some cases, exhibit discontinuities similar to terrestrial alluvial soils. Alluvial floodplain soils exhibit a number of discontinuities and buried surfaces that are considered soil horizons and are important diagnostic criteria in Fluvents and Fluvaquents (Soil Survey Staff, 1998). Organic carbon (OC) data from nine Sinepuxent Bay sediment profiles presented in Fig. 3 indicate that four of the nine profiles (A-Rep, B-Rep, H-Rep, and J-Rep) have marked increases in organic carbon content associated with buried surface horizons. Thus, the burial of old surfaces due to the addition of mineral material to sediment profiles is directly analogous to terrestrial sedimentation processes on floodplains. Regardless of whether considered a process leading to horizon differentiation or not, the potential effect of the addition of mineral material on soil classification and genesis appears to be equally important in both submersed and terrestrial environments.

Table 1. Field morphological description of soil profile F-Rep, Sinepuxent Bay, Maryland (Pedon S97MD047-001).

Horizon	Depth	USDA texture class	Matrix color (moist)	Redoximorphic features		Organic fragments		Shells	Structure	Consistence (moist)	*n*-value	Boundary
				Color	Conc.		Color					
	cm					%		%				
Ag	0–5	S	N 2.5/			5	10YR 2/1	2	sg	1		a
Cg1	5–11	S	5Y 3/1	N 2/	f2d	2	N 2/	5	sg	1		a
2Cg2	11–24	SiC	5Y 3/2	5GY 4/1	f1d				m	fi	>1.0	c
2Cg3	24–57	SiCL	10B 4/1						m	fi	>1.0	c
2Cg4	57–92	SiC	5Y 4/2						m	fi	>1.0	c
Oeb	92–122	Mpt	5Y 3/2			20	7.5YR 3/2					g
Oab	122–139	Mk	N 2.5/									

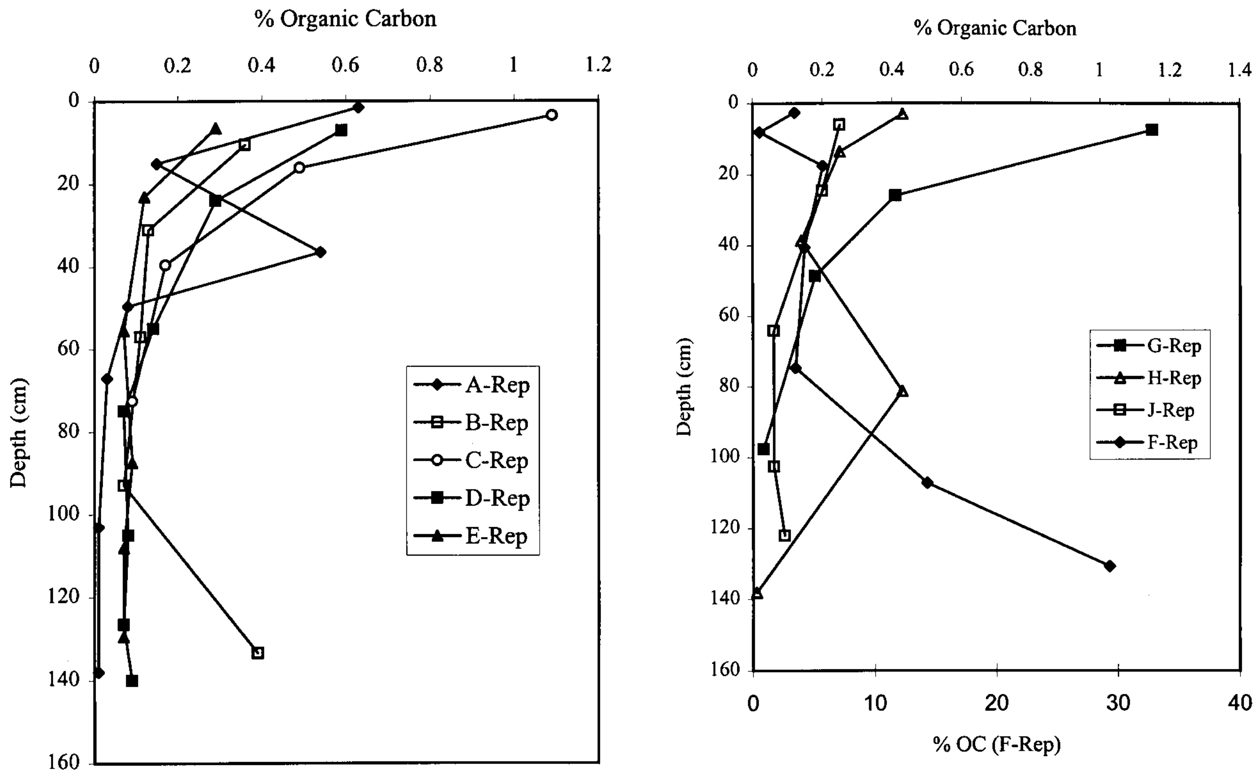

Fig. 3. Organic carbon content with depth for nine sampled representative pedons in Sinepuxent Bay, Maryland.

The presence of benthic faunal remains is one of two primary examples of the pedogenic addition of material of biological origin in Sinepuxent Bay sediments. Shell fragments observed in sediment profiles were identified as the remains of oysters (*Crassostrea virginica*) and various bivalve mollusks such as hard clams (*Mercenaria mercenaria*), jacknife clams (*Ensis directus*), and razor clams (*Tagelus* sp.). Shells were observed in 70 profile descriptions (83%) with quantities ranging from 1 to 40%. Fully intact shells of the marsh periwinkle snail (*Littorina irrorata*) were observed in 17 profile descriptions (20%) at depths ranging from 18 to 110 cm. In addition, live in situ hard clams (*Mercenaria mercenaria*) were observed at over one-half of profile description sites and within one of the vibracore sampled profiles. While visible in field descriptions, the quantity of $CaCO_3$ contributed by these organisms was generally small. Analysis of nine representative profiles showed calcium carbonate levels of $<0.6\%$. In some environments, carbonates may precipitate from seawater, but in this site they are mainly biogenic. The addition of biogenic carbonates might be considered by some a sedimentary phenomena if shell producing benthic organisms did not occur in the area. However, because many of these shells are being added to the profile as a result of in situ benthic organisms, the presence of shell fragments represent legitimate pedogenic additions.

Perhaps the strongest evidence for pedogenic additions lies in the organic components. The addition of organic debris is evident in the morphological description of partially decomposed organic fragments in 65 sediment profiles (77%), with quantities ranging from 1 to 80%. Larger fragments that could be identified included eelgrass (*Zostera marina* L.) blades and saltmarsh cordgrass (*Spartina alterniflora* Loisel.) stems. Organic carbon data from nine Sinepuxent Bay sediment profiles are presented in Fig. 3. All nine sediment profiles exhibit depth functions which are remarkably similar to those of the terrestrial soils. Elevated levels of OC in the surface layers accompanied by (sometimes irregular) decreases with depth are exactly what are found in terrestrial analogs. These data suggest that epipedons are forming as a result of pedogenic processes. Thus, the accumulation of shells of biological origin, vegetative debris, and organic matter, and the development of A horizons in Sinepuxent Bay sediments constitute significant evidence of the process of pedogenic additions.

Pedogenic Losses

Losses, or removals, represent another pedogenic process cited by Simonson (1959). Removals in terrestrial soils occur mainly through the processes of leaching, seepage, erosion, and organic matter decomposition. The most common examples of losses cited in terrestrial soils are those associated with leaching and seepage. In shallow water sediments, leaching and seepage may not be important because of the low hydraulic gradient inherent in a permanently submersed environment.

A loss which frequently occurs in shallow water sediments is that associated with erosion. Erosion from a sediment surface is much more difficult to quantify directly than erosion in a terrestrial setting where detached particles can be captured and measured. In a submersed environment, particles originate from both the sediment surface and input from streams carrying eroded terrestrial material. Causes of sediment surface erosion include storm events, wave agitation, tidal currents, and wind generated waves (Madsen and Warnke, 1983). An indirect method of measuring erosion is through the measurement of total suspended solids (TSS) in the water column. Total suspended solids is a partial indicator of the amount of material being eroded from the sediment surface and resuspended. Young (1971) showed that over 50% of suspended sediment settling out of the water column originated as material eroded from the sediment surface. Average TSS in Sinepuxent Bay in early June 1996 was approximately 140 mg/L while in November 1996 the average value was only 63 mg/L. Because eelgrass, the dominant vegetation in Sinepuxent Bay, is a temperate climate seagrass and is near the southern limit of its habitat (Sculthorpe, 1967), highest productivity occurs in the spring and fall, while dieback usually occurs during the hotter summer months (Chesapeake Bay Program, 1991). A dieback of vegetation exposes the bay bottom surface to the erosive forces of tidal currents and wave agitation. The large increase in TSS in June may reflect an increase in sediment surface erosion attributable to a decrease in vegetation. While somewhat speculative, the TSS data, at the least, support the intuitive concept that erosion is occurring. Although considered a pedogenic loss by Simonson (1959), erosion may not necessarily promote horizon differentiation.

In contrast to the TSS data and its inference of erosion, a more pedologically significant loss from shallow water sediments concerns the decomposition of organic matter. Primary production in North Carolina eelgrass meadows is reported to be 350g C/m^2/yr with approximately 20 to 50% in below ground components (Zieman and Wetzel, 1980). Marshall (1970) found that organic matter imported into the system could contribute an additional 275g C/m^2/yr. Burkholder and Doheny (1968) found that more than 60% of fresh eelgrass detritus was degraded or consumed by microbes in approximately 3 mo, a rate roughly comparable to terrestrial systems (Brady and Weil, 1996). The combination of these processes results in relatively stable sediment OC levels that commonly range from 0.5 to 2.0% (Young, 1971). Surficial sediment layers sampled in Sinepuxent Bay exhibited OC contents of 0.25 to 3.45%. The long-term observation that sediment organic matter accumulates at a very slow rate (Marshall, 1970) suggests that bacterial decomposition of detritus results in the transfer of carbon and other nutrients out of the sediment system. Organic carbon values would be significantly larger if loss through microbial decomposition was not occurring. Thus, the continuous pedogenic addition and loss of organic matter is in part responsible for the development of sediment surface layers with relatively low, but stable, organic carbon levels.

Pedogenic Transfers

Examples of transfers cited by Simonson (1959) and Fanning and Fanning (1989) include eluviation, diffusion, and bioturbation. Although the classical concept of eluviation (or leaching) has previously been discussed as inapplicable in permanently submersed environments, evidence of diffusion and bioturbation were found in Sinepuxent Bay sediments.

Diffusion occurs in terrestrial soils when dissolved ions (or molecules) "move from zones of higher concentration to zones of lower concentration leading to a build-up of the substance in a given part of the soil if a mechanism is operating there to take the ions or molecules out of solution" (Fanning and Fanning, 1989). The light brown color common to many sediment surface layers is an indication of oxygen diffusion across the sediment–water column interface (Fenchel and Riedl, 1970). This zonation is generated as a balance between consumption of oxygen by benthic micro-organisms during organic matter decomposition, and the diffusion of oxygen from the overlying water column into the sediment surface layer. In the absence of burrowing benthic organisms, the "light brown oxidized layer" would range up to a few millimeters in thickness, depending on sediment surface texture (Fenchel and Reidl, 1970). The process of diffusion alone would be of very limited magnitude in the formation of soil horizons. But, bioturbation, typically considered a process opposing horizon development, appears to work together with diffusion processes in promoting horizon differentiation.

In some terrestrial systems, bioturbation such as by ants, termites, earthworms, and crustaceans can lead to soil horizons with distinct chemical and physical properties (Thorp, 1949). In shallow water sediments, the activity of burrowing benthic organisms (such as tubeworms, clams, or scallops) can lead to the formation of an oxidized surface layer up to 10 to 20 cm in thickness. This is a result of both the direct transfer of oxygen by the organisms and an increase in oxygen diffusion due to intensive biogenic mixing and irrigation of tubes and burrows (Rhoads, 1974). Morphological descriptions of

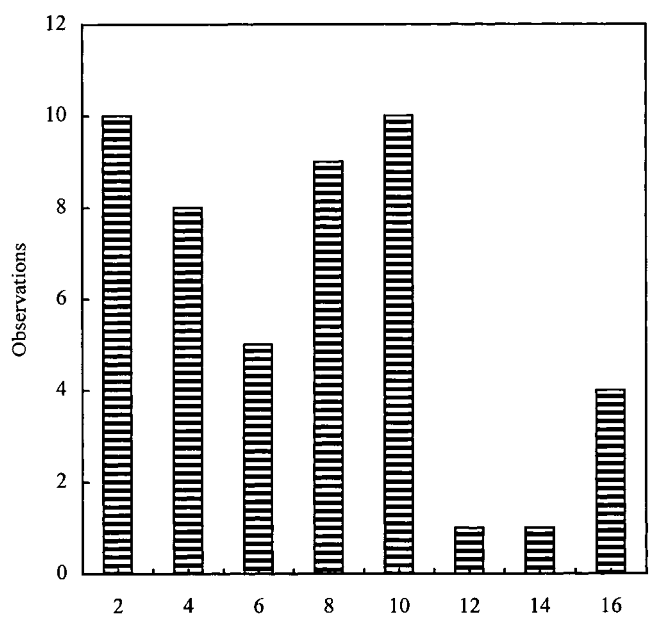

Fig. 4. Frequency distribution of C:N ratios of all sample soil horizons containing greater than 0.10% organic C.

sediment profiles in Sinepuxent Bay indicated at least 18 surface layers (21%) that exhibited high chroma (three or greater) colors. These layers were often 8 to 15 cm in thickness and had abrupt boundaries to low chroma (two or less) layers directly below. The thickness of these surface layers is an order of magnitude larger than would normally be expected in an undisturbed sediment, and is the result of the combination of diffusion and bioturbation transfer processes. Morphological evidence of bioturbation includes the observations of live tubeworms (*Spiochaetopterus oculatus*), mudworms (*Scolecolepides viridis*), hard clams, and worm casts (burrows) in the upper 25 cm of 27 profiles (32%). Thus, the processes of diffusion and bioturbation in tandem are evidence of pedogenic transfers that promote horizon differentiation.

Pedogenic Transformations

The fourth pedogenic process conceptualized by Simonson (1959) is that of transformations. Transformations in terrestrial soils typically are conceptualized as changes in either the organic or mineral fractions. Evidence of transformations in Sinepuxent Bay sediments can be found in both of these components.

One example of a significant transformation occurs in sediment organic matter. A common method of documenting organic transformation is through the use of carbon:nitrogen (C:N) ratios. Typical C:N ratio data for fresh SAV residues are approximately 20:1 to 30:1 (Levington, 1982). These values are similar to C:N ratios for terrestrial grasses which range from 20:1 to 37:1 (Brady and Weil, 1996). Microbial decomposition of organic residues in terrestrial soils and sediments results in a lowering of C:N values. For example, C:N ratios in surface horizons of terrestrial soils typically range from 8:1 to 15:1. C:N ratio data from Sinepuxent Bay sediment layers range from 2:1 to 14:1. Of the 48 sediment layers analyzed for C and N, 90% exhibited C:N ratios of less than 10:1 (Fig. 4). The lowering of C:N ratios in Sinepuxent Bay sediments is an indicator of the transformation of fresh organic matter to other humic substances.

Many transformations common to terrestrial soils may not occur in subaqueous environments. But, there are important mineral transformations unique to estuarine systems such as the formation of solid phase sulfides. This process has been termed sulfidization (Fanning and Fanning, 1989), the dominant end product of which is pyrite (FeS_2). Sulfidization commonly occurs in tidal marsh soils and shallow water sediments in areas affected by estuarine waters. The key elements required include sulfate reducing bacteria such as *Desulfivibro* sp., a source of sulfate, a source of reactive iron, organic matter as a microbial substrate, and anaerobic conditions. During this process, iron oxides in the oxidized surface layer are reduced to soluble ferrous iron. At the same time, sulfate from seawater is reduced by microbes during their oxidation of organic matter. The critical by-product of the sulfate reduction is HS^-, which can then react with the iron in solution to form iron-sulfide compounds such as mackanawite (FeS), greigite (Fe_3S_4), and ultimately pyrite (FeS_2). The main zone of sulfide formation within the sediment column occurs below the boundary between the oxygenated surface layer and the anaerobic subsurface layer. Figure 5 shows the pyrite content with depth for all nine sampled profiles in Sinepuxent Bay. In five of the profiles, pyrite content reaches a maximum at depths ranging from 13 to 38 cm. In

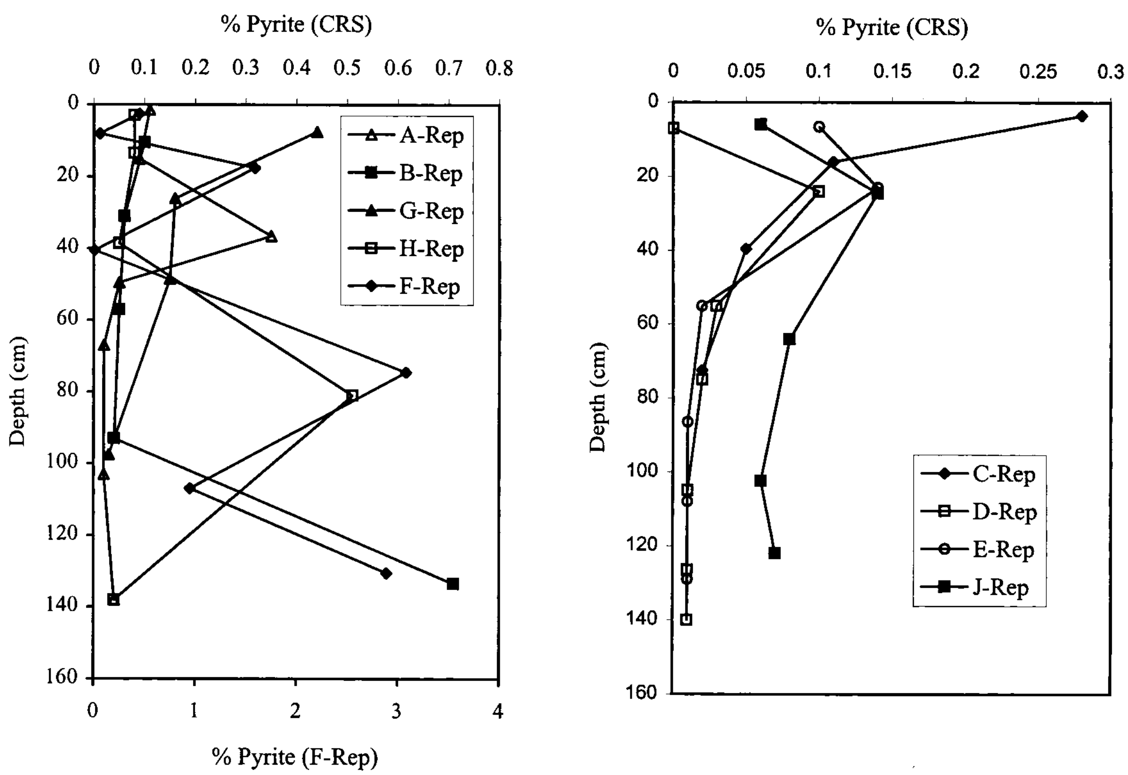

Fig. 5. Pyrite (chromium reducible sulfide) content with depth for nine sampled representative pedons.

addition, three of the profiles exhibit pyrite maximums at depths ranging from 75 to 140 cm. These deeper peaks coincided with buried A horizons high in organic carbon. This would suggest that pedogenic transformations are not only occurring at present, but also have been active in the past when previous surfaces and their associated redox boundary layers were stable. Sulfidization is clearly an important process in the differentiation of sediment layers.

Revision of the Definition of Soil

The evidence presented above clearly shows that the pedogenic processes of additions, losses, transfers, and transformations are active in shallow water sediments and therefore they should be viewed as *subaqueous soils*. These observations provided the impetus to propose a modification to the definition of soil in *Soil Taxonomy* (Soil Survey Staff, 1975) to accommodate shallow water sediments that support submersed aquatic vegetation. Our proposal was reviewed and adopted by the USDA-NRCS National Soil Taxonomy Committee in early 1998. The new definition of soil, as it appears in the 1998 edition of *Keys to Soil Taxonomy* (Soil Survey Staff, 1998), is shown below:

> Soil in this text is a natural body comprised of solids (mineral and organic matter), liquid, and gases which occurs at the earth's surface, occupies space, and has one or both of the following characteristics: (1) is organized into horizons or layers that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter and/or (2) is capable of supporting rooted plants in the natural environment. This definition is expanded to include soils in areas of Antarctica where pedogenesis occurs, but where the climate is too harsh to support higher plant forms.
>
> The upper limit of soil is the boundary between soil and 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 greater than 2.5 m) for the growth of rooted plants. Soil's horizontal boundaries are where it grades to deep water, barren areas, rock, or ice. In some places the separation between soil and non-soil is so gradual that clear distinctions can not be made.

IMPLICATIONS

The pedological and ecological implications of the evidence of pedogenesis in submersed environments and the change to the definition of soil are numerous and potentially significant in their possible applications. This study provides the first comprehensive scientific evidence to confirm previous conceptual proposals that shallow water estuarine sediments are subaqueous soils. This not only expands the "horizontal" boundary of pedology, but also opens significant research opportunities in other facets of soil science and estuarine ecology. The development of a mapping protocol (Demas and Rabenhorst, 1998) based on the soil-landscape paradigm (Hudson, 1992) could be applied for the purposes of subaqueous soil resource inventories. In conjunction with estuarine ecologists, soil scientists could help further our understanding of the distribution and vigor of benthic floral and faunal populations in relation to subaqueous soil characteristics and distribution. Development of subaqueous soil maps could ultimately help focus SAV, clam, oyster, and scallop restocking efforts in estuarine areas with suitable subaqueous soils. Subaqueous soil resource inventories could also be significant to identifying estuarine areas with hazards associated with the disposal of dredge materials with a high potential for acid-sulfate weathering. We believe that subaqueous soils represent a new frontier in soil science and that the development of subaqueous soil resource inventories would make a significant contribution to global estuarine restoration efforts.

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