

Chemical Aspects of Soil

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Introduction

The lithosphere or the solid outer mantle of the earth comprising the outer portion of the earth's crust is exposed to the atmosphere over one-quarter of the area of the globe and covered by the hydrosphere over the remainder. Where the earth's rocks are exposed they, however, usually are in close contact with water and living organisms (the biosphere). The physically and chemically weathered components of the exposed lithosphere form the unconsolidated surface usually known by geologists as the regolith. Further weathering and upward or downward translocation of soluble components in the presence of living organisms and their detritus often result in the formation of an orderly sequence of horizons (Birkeland [4]). Soil is characterized by the ability to support plant and microbial life and the formation of distinct recognizable pedological features across most of the earth's non-aqueous surface.

The interaction of the components plays as great if not a greater role than the chemical characteristics of the individual parts in determining the role of the earth's surface in environmental geochemistry. An understanding of this role can best be obtained from knowledge of the interrelated structure and composition. This chapter includes some indication of the geochemical classification and distribution of the elements, a discussion of the major components of soils, and information on the mechanisms of weathering reactions and soil formation.

Composition of the Earth's Crust

Geochemical Classification and Distribution of the Elements

The elements can be classified into five main groups according to their geochemical character (Rankama and Sahama [34]). *Lithophile elements* ion-

Table 1. The average amounts of the elements in crustal rocks (Berry and Mason [3])

Element ^a	Geochemical classification ^b	$\mu\text{g g}^{-1}$	Element	Geochemical classification	$\mu\text{g g}^{-1}$
O	At, Bi, Li	466,000	Hf	Li	5
Si	Li	277,200	Dy	Li	5
Al	Li	81,300	Sn	Si	3
Fe	Ch, Si	50,000	B	Li	3
Ca	Li	36,300	Yb	Li	3
Na	Li	28,300	Er	Li	3
K	Li	25,900	Br	Li	3
Mg	Li	20,900	Ge	Si	2
Ti	Li	4,400	Be	Li	2
H	At, Bi, Li	1,400	As	Ch	2
P	Bi, Li, Si	1,180	U	Li	2
Mn	Li	1,000	Ta	Li	2
F	Li	700	W	Li	1
S	Ch	520	Mo	Si	1
Sr	Li	450	Cs	Li	1
Ba	Li	400	Ho	Li	1
C	At, Bi, Li, Si	320	Eu	Li	1
Cl	Li	200	Tl	Ch	1
Cr	Li	200	Tb	Li	0.9
Zr	Li	160	Lu	Li	0.8
Rb	Li	120	Hg	At, Ch	0.5
V	Li	110	I	At, Li	0.3
Ni	Si	80	Sb	Ch	0.2
Zn	Ch	65	Bi	Ch	0.2
N	At, Bi	46	Tm	Li	0.2
Ce	Li	46	Cd	Ch	0.2
Cu	Ch	45	Ag	Ch	0.1
Y	Li	40	In	Ch	0.1
Li	Li	30	Se	Ch	0.09
Nd	Li	24	A	At	0.04
Nb	Li	24	Pd	Si	0.01
Co	Si	23	Pt	Si	0.005
La	Li	18	Au	Si	0.005
Pb	Ch	16	He	At	0.003
Ga	Ch, Li	15	Te	Ch	0.002
Th	Li	7	Rh	Si	0.001
Sm	Li	7	Re	Si	0.001
Gd	Li	6	Ir	Si	0.001
Pr	Li	6	Os	Si	0.001
Sc	Li	5	Ru	Si	0.001

^a Omitting those present in less than $0.001 \mu\text{g g}^{-1}$: Ne, Kr, Xe and the short-lived radioactive elements

^b At = Atmosphile; Bi = Biophile; Ch = Chalcophile; Li = Lithophile; Si = Siderophile

ize readily or form stable oxyanions and occur mainly in oxygen compounds. *Chalcophile elements* ionize less readily and tend to form sulphides and covalent compounds with Se and Te. *Siderophile elements* do not readily form compounds with O and S and occur mainly as native elements. *Atmophile elements* are present mainly in atmospheric gases. *Biophile elements* tend to be associated with organisms and thus accumulate in the horizons most affected by organisms in soils

The abundance of elements in the earth's crust 10 miles thick decreases in the order: O, Si, Al, Fe, Ca, Na, K, and Mg (Clarke [8], Ahrens [1]). Only these eight elements are present in amounts higher than 1 % (Table 1) and make up nearly 99 % of the earth's crust. The elements Ti, H, P, and Mn, are present in amounts between 0.1 and 1 %. The remaining elements together make up less than 0.5 % of the earth's crust. Nevertheless, many of these trace elements are of concern to plant growth, animal nutrition and health and the well being of mankind (National Academy of Sciences [31, 32]).

Igneous, Metamorphic and Sedimentary Rocks

The earth's crust consists mainly of the lithophile elements which make up the majority of the rocks and are common in silicates and soils. About 80 elements are distributed in approximately two thousand compounds or minerals. Only a few dozen make up the bulk of surficial rocks. The earth's crust consists of 95 % igneous and metamorphic rocks. The remaining 5 % are sedimentary rocks (Clarke and Washington [9]).

The cooling of magma or silicate melts of the lithophile elements has resulted in the formation of *igneous rocks*. They can be classified into two groups, namely, the *volcanic* or extrusive rocks, and the *plutonic* or intrusive rocks. The latter resulted from slow cooling of magma and are thus coarser grained, whereas the former resulted from rapid cooling upon eruption and are thus finer grained. *Metamorphic rocks* are formed through the action of heat and pressure operating on sedimentary and igneous rocks. Common metamorphic rocks are gneiss, mica schists, slates, marble, and quartzite. Other metamorphic rocks of less extensive occurrence are amphibolite, amphibole schist, hornblende schist, chlorite schist and tactite. The interaction of the atmosphere and hydrosphere on the crust of the earth and the subsequent sedimentation process have produced *sedimentary rocks*. Of these sediments, 80 % are shales, 15 % sandstones, and 5 % limestones (Clarke and Washington [9]). Sedimentary rocks tend to accumulate near the interface of the crust with the hydrosphere and atmosphere, and cover approximately three-fourths of the land area of the earth. The significant variations in mineralogical and chemical composition of these three rock types (Wedepohl [46]) are among the factors affecting soil formation (Jackson [21]) and the quality of our environments (Tourtelot [44]).

Geological Classification of Parent Materials

Parent materials of soils can be classified into two major groups, namely, *sedentary* and *transported*. Sedentary or residual parent materials lie in their original position above bedrocks for centuries. These materials are widely distributed on all the continents and have usually been subjected to long and often intense weathering. Parent materials can be transported and deposited by gravity, water, ice or wind leading to the formation of transported parent materials. They include *colluvial*, *alluvial*, *marine*, *lacustrine*, *glacial*, and *aeolian* deposits.

Colluvial debris is composed of the rock fragments detached from the heights above and carried down the slopes mainly by gravitational force. These materials are generally not of great importance in the formation of productive soils. Alluvial sediments are deposited by streams. Three general classes of alluvial deposits are flood plains, alluvial fans and delta. The soils derived from such sediments usually are very fertile. The products of deposition in the oceans, seas and gulfs are marine sediments. These deposits have been worn and weathered by many natural processes and thus usually carry less of the mineral nutrient elements. Despite this, their soils when adequately managed support a great variety of crops.

The materials deposited directly by the ice are glacial tills and are a mixture of rock debris of great diversity, particularly particle size. The soils derived from such parent materials are thus most heterogeneous. Glacial outwash plains are formed by streams heavily laden with glacial sediments. This type of sediment is generally assorted and consequently of great variety in texture.

Wind erosion results in the formation of aeolian deposits. There are three

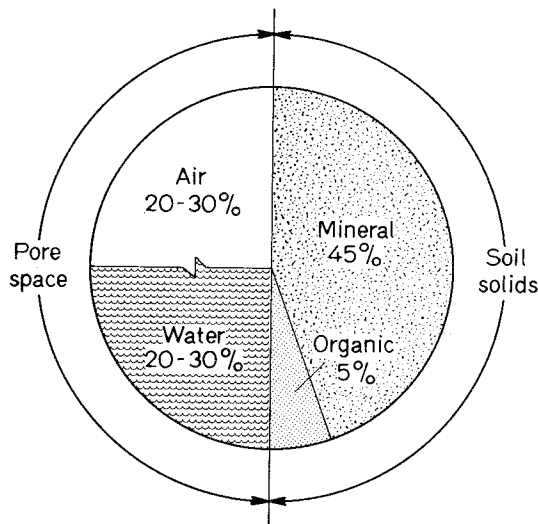


Fig. 1. Volume composition of a silt loam surface soil when in good condition for plant growth (Brady [6])

types of such deposits, namely, loess, volcanic ash and sand dunes. The wind-blown material, termed loess, is deposited in the uplands; the thickest deposits are present in the place where the valleys are widest. Loess has given rise to soils of considerable diversity. Loess soils thus have great differences in fertility and productivity. Soils derived from volcanic ash are light and porous and often have limited agricultural value. Sand dunes support little vegetation under most conditions.

Major Components of Soils

Soils consist of four major components—mineral and organic components, water and air (Fig. 1). The proportion of water and air fluctuates greatly under natural conditions, depending on the climatic and other factors. These four major components of soils exist mainly in an intimately mixed condition. Compared to surface soils, subsoils have a lower content of organic components and air and a higher proportion of mineral components and water.

Mineral Components

The inorganic portion of soils is composed of small rock fragments and a wide variety of crystalline and noncrystalline minerals (Table 2). These materials vary in particle size ranging from gravel to clay fractions (Table 3). The sand and silt fractions of soils are dominated by the *primary minerals* which are inherited from the parent igneous and metamorphic rocks. On the other hand, the clay fraction is enriched in the *secondary minerals* which are formed by low-temperature reactions and inherited in soils from sedimentary rocks or formed *in situ* by weathering.

Primary Minerals

Quartz and Feldspars. The most abundant primary minerals in soils throughout the world are quartz and feldspars, just as they are the dominant rock-forming minerals in the earth's crust. Quartz consists of a continuous framework of silica tetrahedra and is the main form of free silica occurring in soils. The silicate minerals comprise the major weight and volume percentage of most soils. Feldspars are anhydrous three-dimensional aluminosilicates containing varying amounts of Na, K, and Ca and occasionally of other large cations such as Ba. The feldspar minerals are found in virtually all soils and sediments and their nature and quantity vary with the type of parent material and the stage of weathering.

Micas and Accessory Minerals. Muscovite and biotite occur extensively in soils and are important reserves of soil K. They exist in soils primarily through inheritance from the parent rock of the soil. Accessory minerals of soils include a wide variety of minerals which occur in small but significant amounts. These accessory minerals are excellent source minerals for many nutrient elements in soils.

Table 2. Common primary and secondary minerals occurring in soils

Mineral group	Mineral name	Chemical formula
Primary Minerals		
Silica minerals ^a	Quartz	SiO ₂
	Cristobalite	SiO ₂
	Tridymite	SiO ₂
	Opal (inorganic origin)	SiO ₂ · nH ₂ O
Feldspars ^b	Alkali feldspars: Microcline and orthoclase	KAlSi ₃ O ₈
	Plagioclase feldspars: Albite	NaAlSi ₃ O ₈
	Anorthite	CaAl ₂ Si ₂ O ₈
Micas	Muscovite	K(Si ₃ Al)Al ₂ O ₁₀ (OH) ₂
	Biotite	K(Si ₃ Al)(Mg, Fe ^{II}) ₃ O ₁₀ (OH) ₂
Accessory minerals	Pyroxenes:	
	Enstatite	MgSiO ₃
	Hypersthene	(Mg, Fe)SiO ₃
	Diopside	CaMgSi ₂ O ₆
	Augite	Ca(Mg, Fe, Al)(Si, Al) ₂ O ₆
	Amphiboles:	
	Tremolite	Ca ₂ Mg ₅ Si ₈ O ₂₂ (OH) ₂
	Actinolite	Ca ₂ Fe ₃ Si ₈ O ₂₂ (OH) ₂
	Hornblende	(Ca, Na) ₂ (Mg, Fe, Al) ₅ (Si, Al) ₈ O ₂₂ (OH) ₂
	Olivines:	
	Forsterite	Mg ₂ SiO ₄
	Fayalite	Fe ₂ SiO ₄
	Apatite ^c	Ca ₁₀ (F, OH, Cl) ₂ (PO ₄) ₆
	Tourmaline	Na(Mg Fe) ₃ Al ₆ (BO ₃) ₃ Si ₆ O ₁₈ (OH) ₄
	Rutile and anatase	TiO ₂
	Zircon	ZrSiO ₄
	Secondary Minerals	
Carbonate minerals	Calcite and aragonite	CaCO ₃
	Mg-calcite	Ca _{1-x} Mg _x CO ₃ , 0 < x < 0.5
	Dolomite	CaMg(CO ₃) ₂
	Nahcolite	NaHCO ₃
	Trona	Na ₃ CO ₃ HCO ₃ · 2H ₂ O
	Soda	Na ₂ CO ₃ · 10H ₂ O
Sulfate, sulfide, and halide minerals	Gypsum	CaSO ₄ · 2H ₂ O
	Epsomite	MgSO ₄ · 7H ₂ O
	Pyrite	FeS ₂
	Jarosite	KFe ₃ (OH) ₆ (SO ₄) ₂
	Halite	NaCl
Layer silicates ^d	Vermiculite	X _{0.55} (Al _{1.15} Si _{2.85})(Al _{0.25} Fe ^{III} _{0.33} Mg _{2.4}) O ₁₀ (OH) ₂ · nH ₂ O
	Smectite	X _{0.4} (Al _{0.15} Si _{3.85})(Al _{1.3} Fe ^{III} _{0.45} Mg _{0.25}) O ₁₀ (OH) ₂ · nH ₂ O
	Chlorite	(AlSi ₃)AlMg ₅ O ₁₀ (OH) ₈
	Kaolinite	Si ₂ Al ₂ O ₅ (OH) ₄
	Halloysite	Si ₂ Al ₂ O ₅ (OH) ₄ · 2H ₂ O

Table 2 (continued)

Mineral group	Mineral name	Chemical formula
Crystalline oxides, oxyhydroxides and hydroxides	Gibbsite	$\alpha\text{-Al(OH)}_3$
	Boehmite	$\alpha\text{-AlOOH}$
	Goethite	$\alpha\text{-FeOOH}$
	Hematite	$\alpha\text{-Fe}_2\text{O}_3$
	Lepidocrocite	$\gamma\text{-FeOOH}$
	Maghemite	$\gamma\text{-Fe}_2\text{O}_3$
	Pyrolusite	$\beta\text{-MnO}_2$
Noncrystalline mineral components	Allophane	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot n\text{H}_2\text{O}$
	Imogolite	$\text{Al}_2\text{O}_3 \cdot \text{SiO}_2 \cdot 2.5\text{H}_2\text{O}$
	Opal (biogenic origin)	$\text{SiO}_2 \cdot n\text{H}_2\text{O}$
	Ferrihydrite	$\text{Fe}_5\text{HO}_8 \cdot 4\text{H}_2\text{O}$
	Other noncrystalline hydrous ^c oxides and hydroxides of Al and Fe	

- ^a These minerals contain impurities (e.g., Al, Fe, Ti, Na, K, Mg and Ca) which increase in magnitude from quartz to opal due to increased microporosity (Wilding et al. [47])
- ^b Alkali feldspar crystals of soils are perthitic in nature and stores of numerous trace elements (Huang [20])
- ^c Apatite is the most common primary mineral carrier of phosphorus, but occurs also in calcareous sediments (Jackson [21])
- ^d Chemical formulae of layer silicates vary with structural types and isomorphous substitution; imperfectly ordered micas are common in soils derived from sedimentary rocks (Jackson [21]; Gieseking [16])
- ^e The noncrystalline state is stabilized by clay minerals (Rich [35]) and a series of inorganic and organic ligands (Luciuk and Huang [29]; Schwertmann and Taylor [42]; Kwong and Huang [28]; there is no definite composition)

Table 3. Classification of soil particles according to size (International Society of Soil Science)

Name of separate	Size range (mm)
Clay	<0.002
Silt	0.002-0.02
Fine sand	0.02-0.2
Coarse sand	0.2-2.0
Gravel	>2.0

Secondary Minerals

Carbonates, Sulfur-Bearing Minerals, and Halides. The most abundant carbonate mineral of soils is *calcite* which is inherited from the parent rocks of soils or formed in subsoils of subhumid and more arid regions. Depending on pH and the CO_2 pressure of the soil solution, some calcite is dissolved, providing a source of available Ca. *Gypsum* is the most common soil sulfate mineral and accumulates in semiarid and arid regions, frequently beneath the horizon in

which calcium carbonate is accumulated. Gypsum has a relatively high solubility and rate of dissolution compared to silicates. Sulfide minerals, such as *pyrite*, are formed under reducing conditions in the presence of organic matter. The activity of sulfate-reducing bacteria is extremely important in the distribution of sulfide minerals in the soil fabric. The only important halide mineral in soils is *halite* which may form crusts on soil surfaces.

Layer Silicate Minerals. Layer silicates or phyllosilicates play a prominent role in determining the physical and chemical properties of most soils. The two coordinating units are basic to the crystal structure of these minerals. The first is the silicon tetrahedral sheet and the second the octahedral sheet of Al, Fe or Mg. Different combinations of these two types of sheets yield the structures of various layer silicates of importance in soil environments: (1) 1:1 (tetrahedra:octahedra) type minerals, (2) expansible 2:1 type minerals, (3) nonexpansible 2:1 type minerals, and (4) 2:2 type minerals.

The common layer silicates occurring in soils are *mica*, *vermiculite*, *smectite*, *chlorite*, *kaolinite* and *halloysite*. These specific mineral groups do not always occur independently of the other. Several layer silicates are likely in an intimate mixture. Because of structural similarities, they often occur in a mixed order of stacking in which an individual crystal may consist of two or more layer silicates. These assemblages of layer silicates are commonly referred to as *mixed-layer* or *interstratified* minerals. Furthermore, it is important to recognize that hydroxy forms of Al and Fe play significant roles in modifying the physical and chemical properties of clay minerals, particularly vermiculite and smectite. Hydroxy interlayered minerals are also known as *intergradient layer silicates* and are common in soil environments.

Crystalline Oxides, Hydroxides, and Oxyhydroxides and Noncrystalline Mineral Components

The most common crystalline oxide minerals in soils are gibbsite, hematite, goethite, and pyrolusite. Notable noncrystalline inorganic components are allophane, imogolite and hydrous oxides of Al, Fe, Si, and Mn. They are usually low in amount in soil environments, but their importance in determining soil properties and transformations of nutrients and pollutants in terrestrial systems can never be over-emphasized.

Organic Components

Organic Matter. Organic matter plays both a direct and an indirect role in the determination of pedogenic characteristics and formation of soil horizons. It is also a major factor in soil fertility, the retention and deactivation of anthropogenic organic chemicals introduced into the environment, and the type and amount of organic constituents in the weathering process and in the translocation of clays and sesquioxides (Russell [36]).

The diverse mixture, that includes the *soil biomass*, partially degraded plant, animal and *microbial components* and the soil humic constituents,

comprises soil organic matter. The recognizable plant and microbial components constitute 15–25% of the total soil organic carbon in the A horizon of cultivated soils and a large proportion in natural grassland and forest ecosystems. Large plant and animal residues can be removed from the system before analysis. However, most microorganisms and fine root hairs are very small in size. They together with the root exudates are intimately associated with the colloidal components and no known techniques for their separation are presently available. Fractionation of soil humic constituents therefore usually fractionates the microbial components comprising 1–3% of the soil carbon into the different soil fractions regardless of the method of analysis.

Between 52–98% of the organic carbon is associated with the clay and silt sized fractions (Greenland [17]). Much of the remainder is linked to the metal oxides, hydroxides and oxyhydroxides (Schnitzer and Kodama [41]). The classical fractionation technique for soil organic matter includes solubilization and peptization of soil constituents in sodium hydroxide or sodium pyrophosphate. The soluble materials comprise two major fractions, the low molecular weight materials with fairly high functional group acidity (*fulvic acids*) are not precipitated at pH 2, whereas the larger *humic acids* with molecular weights of 20,000 to 100,000 are precipitated. The materials that are so intimately associated with the clays that they are not removed by the basic solution or sequestering agents are known as *humins*. Removal of the clay with agents such as hydrofluoric acid results in the fractionation of the humin into fulvic and humic acids as well as insoluble portions of insect remains, charcoal, etc. (Kononova [25]).

Table 4 shows that humic acids isolated from a wide range of soils have a carbon content ranging from 53.6 to 58.8% with an average of 56.2%. The fulvic acids have a lower carbon content and also show greater variability in

Table 4. Characteristics of soil organic fractions extracted from a wide range of soil types. Includes the range of values measured. (Adapted from Schnitzer [39])

	Humic acids	Fulvic acids
Element (%)		
C	56.2±2.6	45.7±5.0
H	4.7±1.5	5.4±1.6
N	3.2±2.4	2.1±1.2
S	0.8±0.7	1.9±1.8
O	35.5±2.8	44.8±5.1
Functional groups (meq/g)		
Total acidity	6.7±1.1	10.3±3.9
CO ₂ H	3.6±2.1	8.2±3.0
Phenolic OH	3.9±1.8	3.0±2.7
Alcoholic OH	2.6±2.4	6.1±3.4
Quinonoid C = O and ketonic C = O	2.9±2.8	2.7±1.5
OCH ₃	0.6±0.3	0.8±0.5

composition. They have higher hydrogen, sulphur, and oxygen, but lower nitrogen contents. This is expressed in the functional groups with fulvic acids having a much higher total acidity, carboxylic acid content and alcoholic OH's than the humic acids isolated from the same soil (Schnitzer [39]).

Humic and fulvic acids behave like linear flexible polyelectrolytes that are readily aggregated at low pH with the aid of hydrogen bonding, van der Waal's interactions and interactions between the π electron systems of adjacent molecules (Flaig et al. [15]). Fulvic acids at pH values above 2–3 occur as elongated fibers and bundles of fibers with a relatively open structure. With increases in pH, the fibers tend to mesh into a woven network yielding a sponge-like structure. Humic acids show similar structures but because of the lower solubility in water the same structures are observed over a narrower pH range.

Soil organic constituents can be separated into a number of subgroups depending on the soil climate and inorganic constituents (Kuwatsuka et al. [27]). One of the major criteria of a series of papers which studied 37 different humic acids was the degree of humification which is a measure of the light absorbed at 600 nm per unit of carbon, i. e., the darkness of the humic acid solution. The H:C and the O:C ratio also are of significance as shown in

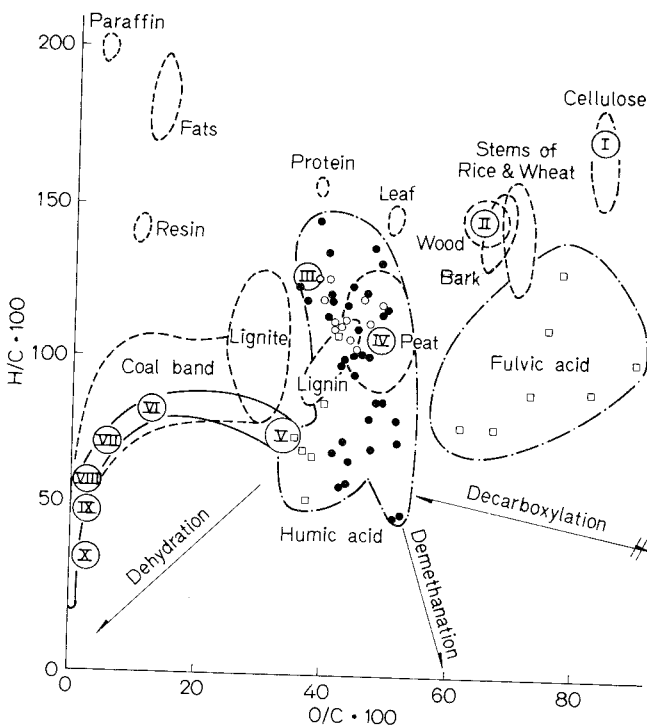


Fig. 2. Atomic H/C versus O/C diagram. I, Cellulose; II, Wood; III, Lignine; IV, Peat; V, Brown coal (Lignite); VI, Low rank bituminous coal; VII, Medium rank bituminous coal; VIII, High rank bituminous coal; IX, Semi-anthracite; X, Anthracite. (From Kuwatsuka et al. [27])

Fig. 2 which compares the oxygen to carbon and hydrogen to carbon ratio of humic and fulvic acids to other organic materials in nature.

The dark amorphous multicomponent humic system never occurs in pure form but is intimately associated with other organic compounds and with the mineral soil colloids. The term *heteropolycondensate* best describes the series of related acidic mycels in which the aromatic rings are bridged by $-O-$, $-NH-$, $-N-$, $-S-$, linkages. Formation of humic material is not enzymatically controlled but is the result of polycondensation of a wide range of microbially produced and plant degradation products. Physical and chemical characteristics of the environment at the time of formation greatly affect the humic structures and these materials cannot be expected to be uniform in structure but are a series of closely related structures. The type of structure suggested by Stevenson ([43], Fig. 3) presents the known characteristics and components of

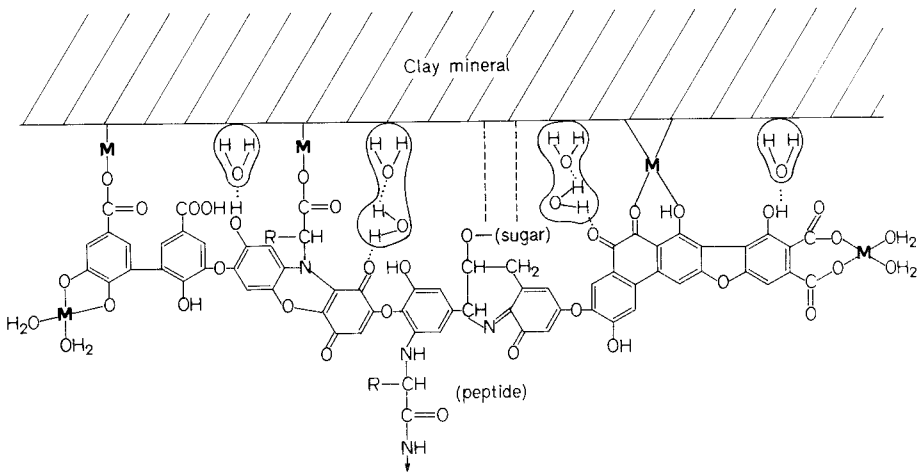


Fig. 3. Clay-metal-organic matter complex

these materials as they interact with mineral constituents through a series of linkages including hydrogen bonding, cation bridge formation and weaker van der Waal's forces. Although there have been a large number of fractionation studies there is still a significant portion of the nitrogen, sulphur and phosphorus of soil organic compounds that has not been identified.

Many of the carbohydrates and alkanes are found within the fulvic acids. However, the proteinaceous materials as well as the aromatics are distributed throughout the fulvic and humic acids and humin. Nitrogen is present primarily as amino acids, amino sugars, nucleic acids and cyclic nitrogen within the humic material (Haider et al. [18]). The known groups of phosphorus compounds in soil include the inositol phosphates, nucleic acid derivatives, sugar phosphates, phosphoproteins and phospholipids (Halstead and McKercher [19]). Although some of the organic sulphur is associated with amino acid carbon in the form of C-S linkages, the majority of the sulphur is found as

C-O-S linkages (ester sulphates). These materials are found in a number of compounds such as sulphated polysaccharides which tend to accumulate in the fulvic fractions.

Content and Turnover of Soil Organic Constituents. Studies of Organic matter in various soils have shown that the tropics contain humic materials at great depths (Bohn [5]), and the organic matter contents of tropical soils are usually at least as high as that of temperate woodlands but usually do not attain the levels of temperate grasslands. Plant residues which are the major source of soil organic matter are fairly rapidly decomposed with half-lives varying from days to months (Paul and van Veen [33]). The living organisms in the soil (the biomass) are comprised primarily of bacteria and fungi. The weight of these usually equals in weight the amount of carbon that enters the system in one year. On the average it turns over less than once during a growing season (Jenkinson and Ladd [23]), but the diverse microbial population varies in its growth rate. Bacteria capable of growth on readily available substrates can double their mass within hours, whereas the majority of the soil population is in a resting state and persists for long periods on minimal exogenous carbon supplies.

Microbial by-products and resistant plant residues adsorbed to soil particles have turnover times in terms of years. The humic materials are more resistant. Carbon dating has indicated that the fulvic acids have turnover times in hundreds of years, whereas the humins and humic acids usually

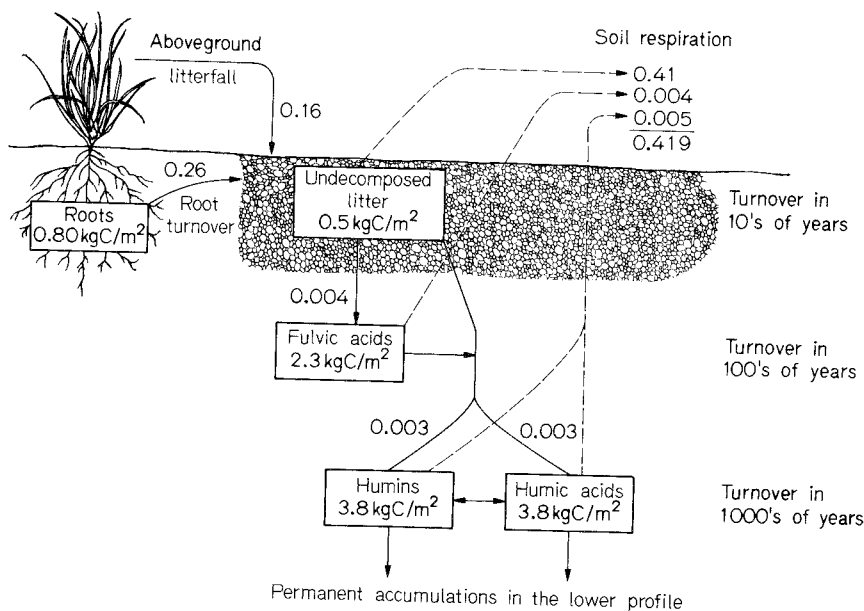


Fig. 4. Detrital carbon dynamics for the 0–20 cm layer of a chernozem grassland soil. Carbon pools (kgC m^{-2}) and annual transfers ($\text{kgC m}^{-2} \text{ yr}^{-1}$) are indicated. Total profile content to 20 cm is 10.4 kgC m^{-2} . (From Schlesinger [38])

approach a thousand years in their turnover time (Paul and van Veen [33]). Figure 4 shows the distribution of carbon in the various fractions and the annual transfers for a grassland chernozem. Although the humins and humic acids comprise by far the majority of carbon within a system, their very slow turnover rate means that they only contribute a small proportion to the annual cycling of carbon within the soil. In this diagram the undecomposed litter estimate also includes the soil biomass and microbial metabolites which together with the plant residues constitute the active fraction of organic matter which plays the prominent role in replenishing the majority of nutrients for plant growth and in the cycling of nutrient elements within the geocycle on an annual basis.

Water, Air, and Structure

Soil Water. Soil water is held within soil pores with varying degrees of tenacity depending upon the nature of soil particles and the amount of water present. Soil water can be divided into three types of physical classes, namely, *gravitational*, *capillary* and *hygroscopic*. Gravitational water is that in excess of the field capacity (10^4 to 2×10^4 Pa or 0.1–0.2 bar suction) and occupies the larger pores, thereby reducing soil aeration. Capillary water is held in pores of capillary size and exerts suction between 10^4 and 31×10^5 Pa (0.1 and 31 bars). Water retained tightly by soil particles at suction greater than 31×10^5 Pa (31 bars) is termed hygroscopic and moves primarily in vapor form.

Based on biological classification, there is a relationship between moisture retention and its availability to plants. Gravitational water is of little use to plants. Moisture retained by the soil at tension greater than 15×10^5 Pa (15 bars) is also largely unavailable to plant growth. Water held by soil particles between the field capacity and the permanent wilting coefficient (15×10^5 Pa) is termed *available water*. Soil water dissolves soluble salts and certain organic components making up the soil solution which is so important as a medium to plant life. Therefore, soil water is affected by osmotic as well as matric tensions.

Soil Air. Soil air is the phase of the soil composed of gases. It differs from the atmosphere in many aspects: (1) it is not continuous but is located in the maze of soil pores; (2) it generally has a higher moisture content than the atmosphere; and (3) the content of CO_2 is usually 5 to 50 times higher than the atmosphere. There is a general inverse relationship between O_2 and CO_2 contents and their sum is close to 21% of soil air by volume. The concentration of N_2 in soil air is in the order of 79% by volume and comparable to atmospheric air. Under conditions of poor aeration, N_2O , NO , H_2 , CH_4 , C_2H_4 , and H_2S may be present in soil air (Yoshida [48]; Burford [7]; Bailey and Beauchamp [2]).

The content and composition of soil air is determined by the following factors: (1) the soil-water relationships; (2) the rate of production and consumption of the various gases in the soil; and (3) the rate of exchange between the soil air and atmospheric air (de Jong and Paul [10]). Changes in the content

and composition of soil air have significant effects on the physical environment of soils.

Soil Structure. Soil structure results from aggregation of soil particles. Important factors governing the structural formation are the nature of soil parent material and the physical, chemical and biochemical processes of soil formation. Noncrystalline Al and Fe oxides of the weathering products act as cementing agents in binding soil separates (Kroth and Page [26]; Jones and Uehara [24]). Aluminium oxides are much more effective than iron oxides in promoting the stability of soil aggregates (Saini et al. [37]; El Swaify and Emerson [13]).

Organic matter, particularly polysaccharide, is closely associated with soil aggregation. It may promote soil aggregation through the following linkages: clay-(Al, Fe)-organic matter-(Al, Fe)-clay (Edwards and Bremner [12]). Large organic molecules usually form bonds with several mineral particles, increasing aggregate stability.

There are four major types of soil structure, namely, *platy*, *prism-like*, *block-like* and *spheroidal*. The important changes in physical properties as a result of cultivation are structural rather than textural. Soil condition and characteristics such as bulk density, porosity, aeration, and water movement are much influenced by soil structure.

Weathering Reactions and Soil Formation and Distribution

Parent rocks of soils are disintegrated by physical weathering into rock fragments and the individual minerals of which they are composed. Rock fragments and the minerals therein are further attacked by chemical and biochemical forces. Weathering of minerals through these processes releases nutrients to nourish plants. Residues from the organisms return to the weathering mass and are transformed to humus. During soil forming processes, primary minerals are altered to varying extents or transformed to crystalline secondary minerals, noncrystalline mineral components (Jackson [22]; Marshall [30]) and organomineral complexes (Schnitzer and Kodama [41]), depending on the nature of parent materials, climate, living organisms, topography and time. Crystalline and noncrystalline mineral colloids, humus and living organisms together with life-sustaining water affect markedly the kind and extent of horizon differentiation that occurs in soil environments.

A *soil horizon* is defined as a layer of soil, approximately parallel to the soil surface, with characteristics produced by soil-forming processes (US Soil Conservation Service [45]). In addition to genetic soil horizons, many soils show stratification due to variations in parent material of lithological discontinuities. Designations of master soil horizons are summarized in Table 5. Each soil is characterized by a given sequence of soil horizons. The sequence is referred to as a *soil profile*. Soils which have been developed by various processes vary in many profile characteristics and differ from region to region.

Table 5. Soil horizon designations (FAO-Unesco [14])

Master horizon	Description
H	An organic horizon formed or forming from accumulations of organic material deposited on the surface that is saturated with water for prolonged periods and contains 30% or more organic matter if the mineral fraction contains more than 60% of clay, 20% or more organic matter if the mineral fraction contains no clay, or intermediate proportions of organic matter for intermediate contents of clay
O	An organic horizon formed or forming from accumulations of organic material deposited on the surface that is not saturated with water for more than a few days and contains 35% or more organic matter
A	A mineral horizon formed or forming at or adjacent to the surface that either: (1) shows an accumulation of humified organic matter intimately associated with the mineral fraction, or (2) has a morphology acquired by soil formation but lacks the properties of E and B horizons
E	An eluvial mineral horizon showing a concentration of sand and silt fractions high in resistant minerals, resulting from a loss of silicate clay, iron or aluminium or some combination of them
B	A mineral horizon in which rock structure is obliterated or is but faintly evident, characterized by one or more of the following features: (1) an illuvial concentration of silicate clay, iron, aluminium, or humus, alone or in combination; (2) a residual concentration of sesquioxides relative to source materials; (3) an alteration of material from its original condition to the extent that silicate clays are formed, oxides are liberated, or both, or granular, blocky, or prismatic structure is formed
C	A mineral horizon (or layer) of unconsolidated material from which the solum is presumed to have formed and which does not show properties diagnostic of any other master horizons
R	A layer of continuous indurated rock that is sufficiently coherent when moist to make hand digging with a spade impracticable

Table 6. The nomenclature of the soil units (FAO-Unesco [14])

Soil unit ^a	Nomenclature
Fluvisols	From L. <i>fluvius</i> , river; connotative of floodplains and alluvial deposits
Gleysols	From Russian local name <i>gley</i> , mucky soil mass; connotative of an excess of water
Regosols	From Gr. <i>rhegos</i> , blanket; connotative of mantle of loose material overlying the hard core of the earth; soils with weak or no development
Lithosols	From Gr. <i>lithos</i> , stone; connotative of soils with hard rock at very shallow depth
Arenosols	From L. <i>arena</i> , sand; connotative of weakly developed coarse-textured soils

Table 6 (continued)

Renzina	From Polish <i>rzedzic</i> , noise; connotative of noise made by plough over shallow stony soil
Rankers	From Austrian <i>Rank</i> , steep slope; connotative of shallow soils from siliceous material
Andosols	From Japanese <i>An</i> , dark, and <i>Do</i> , soil; connotative of soils formed from materials rich in volcanic glass and commonly having a dark surface horizon
Vertisols	From L. <i>verto</i> , turn; connotative of turnover of surface soil
Solonchaks	From Russian <i>sol</i> , salt
Solonetz	From Russian <i>sol</i> , salt
Yermosols	From Sp. <i>yerma</i> , desert
Xerosols	From Gr. <i>xeros</i> , dry
Kastanozems	From L. <i>castaneo</i> , chestnut, and from Russian <i>zemlja</i> , earth, land; connotative of soils rich in organic matter having a brown or chestnut colour
Chernozems	From Russian <i>chern</i> , black, and <i>zemlja</i> , earth, land; connotative of soils rich in organic matter having a black colour
Phaeozems	From Gr. <i>phaios</i> , dusky, and Russian <i>zemlja</i> , earth, land; connotative of soils rich in organic matter having a dark colour
Greyzems	From Anglo-Saxon <i>grey</i> ; colour formed by blending of white and black; connotative of white silica powder which is present in layers rich in organic matter, and from Russian <i>zemlja</i> , earth, land; connotative of soils rich in organic matter having a grey colour
Cambisols	From late L. <i>cambiare</i> , change; connotative of changes in colour, structure and consistence resulting from weathering in situ
Luvisols	From L. <i>luvi</i> , from <i>luo</i> , to wash, lessiver; connotative of illuvial accumulation of clay
Podzols	From Russian <i>pod</i> , under, and <i>zola</i> , ash; connotative of soils with a strongly bleached horizon
Podzoluvisols	From Podzols and Luvisols
Planosols	From L. <i>planus</i> , flat, level; connotative of soils generally developed in level or depressed topography with poor drainage
Acrisols	From L. <i>acris</i> , very acid; connotative of low base saturation
Nitisols	From L. <i>nitidus</i> , shiny; connotative of shiny ped surfaces
Ferralsols	From L. <i>ferrum</i> and aluminium; connotative of a high content of sesquioxides
Histosols	From Gr. <i>histos</i> , tissue; connotative of soils rich in fresh or partly decomposed organic matter

^a These units are generally comparable to the "great group" level

By establishing a common denominator between different soil classification systems, the major soil units, which have been recognized in all parts of the world, both in virgin conditions and under cultivation, are combined into one outline. The *soil units* (Table 6) adopted are selected on the basis of present

knowledge of the formation, characteristics and distribution of the soils covering the earth's surface, their importance as resources for production and their significance as factors of the environment.

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