12) Soil Orders

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12) Soil Orders

In chapter 12 the eleven soil orders of Soil Taxonomy are described. Because the Soil Taxonomy is a hierarchical system we will also use a hierarchical structure starting each chapter with a brief summary and adding more and more detail. The requirements, diagnostic horizons, and properties to meet each soil order are given. Additionally, attention is given on the links between processes and properties for each soil order. More information about soil orders, suborders, and the great groups can be looked up in the Keys to Soil Taxonomy (Soil Survey Staff) USDA-NRCS.

Further Reading

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12.1) Alfisols

Summary:

- Vegetation: deciduous forest (prairie, grassland)
- Climate: thermic or warmer, mesic or cooler
- Soil moisture regime: erratic soil moisture regime
- Major soil property: medium to high base saturation
- Diagnostic horizons: albic, argillic (natric, kandic)
- Epipedon: ochric (mollic, umbric)
- Major processes: weathering, eluviation/illuviation

12.1.1) Environmental Conditions

Climate: The climatic conditions under which Alfisols form are thermic or warmer and mesic or cooler. Therefore, most Alfisols are in temperate regions, but these soils are also extensive in tropical and subtropical zones. Alfisols can occur generally in zones with a temperature range from below 0°C to above 22°C. Important for the development of Alfisols is the change between periods of high moisture content and high soil temperature, to break down the primary mineral components and to leach the weathered products, and low moisture content and low soil temperatures, which permit the precipitation or accumulation of the weathered products. Most Alfisols have an udic, ustic, or xerix moisture regime, and many have aquic conditions, but they are not known to have a perudic moisture regime. The suborder of Aqualfs requires higher soil moisture conditions compared to the development of other suborders of the Alfisols.

Vegetation: Most Alfisols are formed under broadleaf decidious forest, but they occur also under grassland and prairie vegetation. In forested ecosystems, the trees deliver the bulk of their annual production of organic matter aboveground, which is different from grassland soils. In those ecosystems the organic matter is enriched by the huge rootsystem of the grass or prairie cover. While present vegetation may be deciduous forest, earlier vegetation may have been grass or conifers.

Relief: In most Alfisols the drainage is not restricted with the water table occuring below the solum during major portions of the nonfrozen period. For instance, the suborder of Aqualfs is often functionally related to landscape position. Alfisols develop under several drainage conditions ranging from excessive on hill crest and steep slopes (e.g Lithic Hapludalfs) to poorly drained footslopes and level plains (e.g. Albaqualfs). Alfisols do not develop on very steep slopes, alluvial floodplains, and very poorly drained depressions. High elevations combined with limited rainfall favor Alfisol formation in the tropics.

Parent Material: The parent material has a major impact on the formation of clay minerals within soil. The resistance to weathering and the composition of primary minerals determine in combination with the other soil forming factors which clay minerals are formed. Generally, a wide variety of clay minerals ranging from kaolinites, hydrous micas, montmorillonites to vermiculites can occur. It should be stressed that several clay minerals do have a potential to adsorb exchangeable bases (high cation exchange capacity), which is a critera that should be met to qualify for an Alfisol. Most Alfisols are present on relative old landscapes (beginning Holocene or older) whereever the supply of primary minerals is plentiful.

Time: Most Alfisols need a longer period of time for development. Several studies postulated that the time to develop Alfisols is at least 200 y, where an argillic horizon is approached, to 1000 y for a clear expression of an Alfisol profile, and even longer periods, depending on the other soil forming factors.

12.1.2) Processes

The weathering of primary mineral components is a prerequisite for further processes to form Alfisols. Water is the master ingredient to accelerate physical and chemical weathering, particularly for hydration, hydrolysis, and oxidation. If the primary minerals are weathering in an alkaline environment then carbonates often initially dominate the weathering products. The release of H^+ ions for Ca^{2+}, Mg^{2+}, and a variety of other cations, from the roots of vegetation fosters also the process of weathering. At the same time, under forest vegetation, most profiles show Ca^{2+} and Mg^{2+} higher in amount in the surface horizon than in horizons below. This may be attributed to recycling through leaf fall and decay. On the other hand, lower Ca^{2+} and Mg^{2+} values in the lower horizons of Alfisol solum can be an indication of more intense weathering.

The litter is decomposed to form an A horizon (decomposition, humification, mineralization). Under deciduous forest often an O and A horizon is found. There is relatively little accumulation of organic matter in the mineral horizons due to cycling of nutrients in the upper horizons. Biocycling of nutrients from B horizons to A and O horizons is an important process in most forested Alfisols. This explains the high content of bases (Ca, Mg, and K) in the ochric epipedon.

Eluviation of clay (in organic and inorganic form) from the A and E horizons in the initial material, of clay formed by mineral weathering, and of clay progressively added in eolian material is a dominant process in the formation of Alfisols. The eluviated material is illuviated in the underlying B horizon (illuviation), i.e., an argillic horizon is formed. Therefore, particularly the E horizon, is depleteted in organic colloids, clay minerals, and / or oxides and hydroxides,i.e., an albic diagnostic horizon is formed. The process of clay translocation is also called lessivage. An erratic moisture regime favors the formation of an argillic horizon, because the processes of weathering and translocation are supported by percolation water and the precipitation of the translocated material by dry moisture conditions.

The details of eluviation and illuviation can highlight the complexity of a variety of subprocesses involved in the development of Alfisols. Leaching of carbonates from the toplayers appear to be a prerequisite before clay can migrate. The presence of exchangeable calcium (from calcium carbonate) flocculates clay particles, creating particles that are too large to be transported in suspension. Removal of the calcium leaves the solum in a condition favorable for the dispersion of clay particles. When the clay particles are dispersed in an aqueous suspension translocation from the A and E horizons into the B horizon occurs with or without aid of complexing organic compounds, and possibly by migration of Si, Fe and Al under the influence of percolating water. Fine clays move more readily than coarse clay, therefore, the fine clay to total clay ratios are typically higher in the B horizon (0.6 - 0.8) than in the A and E horizons (0.3 - 0.6). Freshly formed clays tend to move more readily than older clays. The influence of organic matter on the transport phenomena of clay colloids in soils has been stressed by many authors. Organic matter is known to act as an electron donor for the reduction and solubilization of iron oxides which are leached. Sesquioxides do act as a cohesion agent. Furthermore, the presence of organic acids tends to destabilize the soil micro-aggregates and produce dispersible clays which are subsequently leached.

Argillans (clay coatings) are formed in the B horizon, which are often fewer in the upper B compared to the lower B horizon(s). This can be explained by shrink-swell cycles (freezing-thawing, wetting-drying), soil creep, and biologic mixing, which are more intense in the upper horizon. The precipitation of clays, often with sequioxides and organic matter, in the argillic horizon may be brought about by (i) depletion of percolating waters through sorption by peds, (ii) swelling shuts of voids and consequent slowing of percolating water, (iii) sieve action by clogging of fine pores, (iv) flocculation of the negatively charged clay by positively charged iron oxides in the Bt horizon or by calcium in the higher-base saturation lower solum, and (v) low pH which favors flocculation. The accumulation of clay may be masked by other processes such as pedoturbation.

Additionally, there might be in situ formation of clay minerals in the B horizon by weathering of primary minerals such as feldspars, micas, and ferromagnesian minerals, or by neosynthesis from illuvial weathering products. In young Alfisols the illuviation is the dominant process for the formation of an argillic horizon, whereas through time the in situ formation of clays within the argillic horizon becomes more dominant.

If the accumulation of clay materials in the Bt horizon is high it results in a decrease of percolation and subsequent waterlogging (reducing, anerobic environmental conditions). The slower permeability also favors the in situ weathering of primary minerals to clays. For example, Palexeralfs form on earlier-Pleistocene deposits when clay accumulation and slow permeability is sufficient to cause perching of a seasonal water table in the winter. Under such conditions iron oxide concretions form in horizons affected by a perched water table above dense B horizons.

In most Alfisols there is also a removal of Fe and Al from the E horizon to the B horizon. This can be attributed to the cheluviation of metal ions and organic colloids that form metal-organic complexes which are translocated of metal ions and organic colloids that form metal organic complexes which are translocated.

12.1.3) Properties

A typical Alfisol profile looks like:

- On uncultivated sites: A very thin O horizon is common; on cultivated sites: no O horizon

- Thin A (less than 15 cm), weakly expressed crumb or granular structure

- Moderate thin E horizon (15 - 25 cm), platy structure, light-colored

- B horizon, usually with several subdivisions, which is normally between 25 - 75 cm thick, moderate to strong angular or subangular blocky structure, a lower case 't' is used to denote for an accumulation of silicate clay

Characteristics of the albic diagnostic horizon:

- High in silt-size and larger particles
- High amount of stable minerals such as quartz, tourmaline and rutile
- Absence of organic matter
- Particles are not aggregated
- Higher pH compared to the argillic horizon (pH 6.5 - 7.0)
- Higher Eh compared to the argillic horizon
- Low cation exchange capacity
- Platy structure

Characteristics of the argillic diagnostic horizon:

- Accumulation of clay (organic and mineral colloids). The illuviated materials are deposited on structural aggregates, along root channels and on the surfaces of coarser particles (e.g. argillans)

- Accumulation of iron and aluminium oxides (partly adsorbed to clay minerals)
- The colloidal organic matter is mostly in the form of organo-clay complexes
- Lower pH compared to the albic horizon (pH 4.5 - 6.0)
- Lower Eh compared to the albic horizon
- High cation exchange capacity
- Blocky structure

12.1.4) Classification

The requirements to qualify for an Alfisol are the following:

- High base status: > 35 % base saturation at a depth of 125 cm below the upper boundary of the argillic, natric, or kandic horizon
- An argillic horizon that is not under a spodic or oxic horizon
- Any soil temperature regime is allowed, except pergelic

The suborders of Alfisols are distinguished by soil temperature and soil moisture (Figure 12.1.4). The suborders, great groups, and subgroups of Alfisols are described in the Keys to Soil Taxonomy.

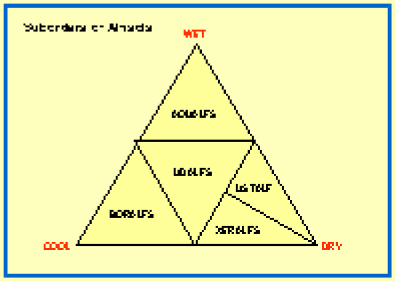

Figure 12.1.4. Diagram showing some relationships between suborders of Alfisols.

Aqualfs: They have aquic conditions for some time in most years within 50 cm of the mineral horizon and redoximorphic features in the upper 12.5 cm of the argillic, natric, or kandic horizon. Their appearance is normally controlled by gray redox depletions and higher-chroma redox concentrations. In some, ground water is near the surface during a considerable part of the year but drops to depths below the argillic (or natric, kandic horizon) in another part of the year. In others, the ground water may be deep most of the year but horizons that have low hydraulic conductivity restrict the downward movement of water and extend the period of saturation. Aqualfs occur in many parts of the world, mostly in small areas in deposits of late-Pleistocene age, where they occupy depressional areas or low-gradient landscapes subject to seasonal high water tables. Nearly all Aqualfs are believed to have supported forests at some time in the past. Most Aqualfs, except those that have a frigid or cryic temperature regime, have some artificial drainage or other water control and are cultivated. Rice is a common crop on Aqualfs that have a thermic or warmer temperature regime.

Boralfs: Boralfs are the more or less freely drained Alfisols of cold regions. They have a cryic temperature regime and an udic moisture regime is considered normal. Boralfs are not extensive. They form in North America, eastern Europe, and Asia above 49° north latitude and in some high mountains south of that latitude. In the mountains, they tend to form below the Spodosols or Inceptisols. Most of them are or have been under a coniferous forest. Characteristically, Boralfs have an O horizon, an albic horizon, and an argillic horizon. A thin A horizon is present in some. In regions of the least rainfall, they are neutral or slightly acid in all horizons and a Bk horizon may underlie the argillic horizon. In many of the more humid areas of their occurence, the lower part of the albic horizon and the upper part of the argillic horizon are strongly or very strongly acid. Boralfs in the U.S. generally developed in Pleistocene deposits, mostly Wisconsinan age and under forest.

Udalfs: Udalfs are the more or less frequently drained Alfisols that have udic moisture regime and a frigid, mesic, isomesic, or warmer temperature regime. They are principally but not entirely on late-Pleistocene deposits and erosion surfaces of about the same age. Some of the Udalfs that are on older surfaces are underlain by limestone or other calcareous sediments. Udalfs are very extensive in the United States and in western Europe. All of them are believed to have had forest vegetation at some time during development. Most Udalfs with a mesic or warmer temperature regime have or had a deciduous forest vegetation and many of the frigid temperature regime have or had mixed coniferous and deciduous trees. Many Udalfs have been cleared of forests and intensively farmed, and as a result of erosion many now have only an argillic or a kandic horizon below the Ap horizon that is mostly material part of the argillic or kandic horizon. Others are on stable surfaces and retain most of their eluvial horizon above the argillic or kandic horizon. Normally, the undisturbed soil has a thin A horizon darkened by humus. A few Udalfs have a natric horizon. Others have a fragipan in or below the argillic or kandic horizon.

Ustalfs: They have an ustic moisture regime and a frigid, mesic, isomesic, or warmer temperature regime. They do not have, near the soil surface, both redoximorphic features with low chroma and aquic moisture regime for some time in normal years or artificial drainage. Moisture moves through most of these soils to deeper layers only in occasional years. If there are carbonates in the parent material or in the dust that settles on the surface, they tend to have a Bk or a calcic horizon below or in the argillic or kandic horizon. The dry season or seasons are pronounced enough that trees are either deciduous or xerophytic. Many of these soils have or have had a savanna vegetation and some were grasslands. Most of these soils are used for cropland of for grazingland. Ustalfs are the Alfisols of subhumid to semiarid regions. Sorghum, wheat, and cotton are common crops. Droughts are common. They occur in the United States mostly on the southern Great Plains. They are common in Africa, India, South America, Austalia, and southeastern Asia. The Ustalfs may be on erosion surfaces or deposits of late Wisconsian age, but many occur on old surfaces. In those soils the minerals have been strongly weathered, possibly in an environment more humid than the present one. At least, the clays in many of these older soils are kaolinitic. The base saturation in them at present probably reflects additions of bases in dust and rain.

Xeralfs: They have xeric moisture regime common of regions that have Mediterranean climate. They are dry for extended periods in summer, but in winter, moisture moves through the soil to deeper layers in at least occasional years, if not in normal years. Small grains, and other annuals are common crops where there is no irrigation. Grapes and olives are also common crops where the climate is thermic. With irrigation, a wide variety of crops can be grown. The Xeralfs formed in South Africa, Chile, Western Australia, Southern Australia and the Western United States. Most border the Mediterranean Sea or lie to the east of an ocean in midlatitudes. In the world as a whole, the Xeralfs are not extensive soils, but in the regions where they occur, they are extensive. The vegetation, before the soils were farmed, was a mixture of annual grasses, forbs, and woody shrubs on the warmest and driest Xeralfs and coniferous forest on the coolest and most moist Xeralfs. Xeralfs formed on surfaces that are different ages. Some formed on erosion surfaces or in deposits of late-Wisconsinan age, and some, as in Australia, are on old surfaces and have characteristics that probably reflect an environment greatly different from the present one. It is common in the oldest Xeralfs that the boudary between the A and B horizons is very abrupt. The epipedon of some Xeralfs is hard and massive when dry.

Great groups and subgroups are classified according to following features:

Alfisol may have (i) a fragipan (e.g. Fragixeralfs, Fragiaquic Paleudalfs), (ii) a duripan (e.g. Durixeralfs, Durudands, Durustands), (iii) a kandic horizon (e.g. Kandiaqualfs), (iv) a natric horizon (e.g. Natraqualfs), (v) a salic horizon (e.g. Salidic Natrustalfs), (vi) a calcic horizon (e.g. Calcic Rhodoxeralfs), (vii) a petrocalcic horizon (e.g. Petrocalcic Natrustalfs), (viii) or plinthite horizon (e.g. Plinthustalfs, Plinthic Paleustalfs).

(i) Fragipans are found in some great groups of Alfisols. It is postulated that the majority of fragipans have developed nearly concurrent with the argillic horizon, sometimes as a part of it, in other cases immediately below. The dense, brittle character of the fragipan is attributed to various cementing agents such as silicate clays, oxides of iron, manganese and aluminum, and colloid silica. These are weathering products of the upper horizons, which are translocated and accumulated in lower horizons. The phenomena of large polygonal cracking commonly observed in the fragipan zone suggests a time of desiccation, probably on a recurring basis, with accumulated in-filling.

Recent research on the formation of fragipans suggest that the 'hydroconsolidation process', i.e., a structure collapse when loaded and wetted may contributed to fragipan formation (Bryant, 1989; Assallay et al., 1998). The classic occurences of hydroconsolidation are in loess soils with a clay content of 5 to 30 %. Fragipans occur more or less at a constant depth of about 40 to 80 cm below the soil surface.

(ii) In some Alfisols there is a duripan, i.e., a horizon of silica cementation. For example, the processes to form duripans are the slow weathering of feldspars and ferromagnesian minerals in older landscapes or rapid weathering of volcanic glass.

(iii) A kandic horizon is a subsoil diagnostic horizon having a clay increase relative to overlying horizons and low activity clays, with <= 16 cmol/kg clay CEC.

(iv) In soils with high Na content the sodium ion is important in the dispersion and mobilization of clay. Under such environmental conditions natric horizons can form, where pH may be as high as 10 or 11. Sodium is a cation which is weakly absorbed and is leached easily. Soil layers high in sodium are dispersed when wet, and show a low permeability and low aeration. Natric horizons are expressed in the great groups of Alfisols, for example, in Natrixeralfs, Natrudalfs, or Natrustalfs. (v) Salic horizons are enriched in secondary soluble salt such that the electrical conductivity exceeds 30 dS/m more than 90 days each year.

(vi) A calcic horizon is a mineral soil horizon of secondary carbonate enrichment that is more than 15 cm thick, has a $CaCO_3$ equivalent of > 150 g/kg. (vii) If a horizon of indurated carbonates occur the formed diagnostic horizon is called petrocalcic. In general, a shift to a drier regime with periods of evaporation would contribute to carbonate accumulation.

(viii) Plinthite is a weakly-cemented iron-rich, humus poor mixture of clay with other diluents that commonly occurs as dark red redox concentrations that form platy, polygonal, or reticulate patterns. Plinthite changes irreversibly to ironstone hardpans or irregular aggregates on exposure to repeated wetting and drying.

A tonguing of the A horizon into the B horizon is also found in some Alfisols. The matrix of the tongues is similar to that of the eluvial horizon. It may be initiated by tree-root penetration and decay. These soils are classified in the great groups of Alfisols, such as, Glossaqualfs, Glossocryalfs, Glossudalfs or in the subgroups of Alfisols, such as Glossaquic Paleudalfs, Glossaquic Natrudalfs, or Glossic Natraqualfs.

Alfisols with vertic soil characteristics, i.e., cracks that are 5 mm or more wide through a thickness of 30 cm or more for some time in most years, and slickensides or wedge-shaped aggregates in a layer 15 cm or more thick that has its upper boundary within 125 cm of the mineral soil surface; or a linear extensibility of 6.0 cm or more between the mineral soil surface and either a depth of 100 cm or a densic, lithic, or paralithic contact, whichever is shallower (e.g. Vertic Natraqualfs).

'Albic' materials, i.e., soil materials with a color white to gray mainly due to the color of primary sand and silt particles and from which clay and/or free iron oxides have been removed, is used to define Alfisols at the subgroup level (e.g. Albic Natraqualfs).

Alfisols with recognizable bioturbation such as filled animal burrows, wormholes, or casts are named 'Vermic' (e.g. Vermic Natraqualfs, Vermic Fragiaqualfs).

Soil color is used to define 'Aeric' - chroma of 2 or more and no redox depletions (e.g. Aeric Kandiaqualfs), 'Udollic' - color value moist of 3 or less (e.g. Udollic Albaqualfs), and 'Rhodic' - a hue of 2.5YR or redder and a value (moist) of 3 or less (e.g Rhodic Kandiustalfs) characteristics of Alfisols.

Epipedons are also used to distinguish Alfisols at the subgroup level: 'Mollic' (e.g. Mollic Natraqualfs), 'Umbric' (e.g. Umbric Fragiaqualfs), or 'Histic' epipedon (e.g. Histic Glossaqualfs). 'Humic' is used for Alfisols with high organic matter content (e.g. Humic Fragiaqualfs).

Soil texture is used to classify Alfisols at the subgroup level: 'Arenic' or 'Grossarenic' show a sandy or sandy-skeletal particle-size class (e.g. Arenic Kandiaqualfs, Grossarenic Kandiaqualfs), 'Psammentic' subgroups show a sandy particle-size class throughout the argillic horizon (e.g. Psammentic Cryoboralfs).

Soils formed in volcanic parent material with low bulk densities (< 1.0 g/cm^3) and more than 35 % fragments coarser 2.0 mm are denoted by 'Andic', 'Aquandic', or 'Vitrandic' (e.g. Andic Palexeralfs, Aquandic Albaqualfs, Vitrandic Fragiudalfs).

Alfisols that have episaturation, i.e., when a soil is saturated with water in one or more layers within 200 cm of the mineral soil surface and also has one or more unsaturated layers with an upper boundary above 200 cm, below the saturated layers(s) the prefix 'Epi' (e.g. Epiaqualfs) is used. Alfisols with wet soil moisture conditions and redox depletions with a chroma of 2 or less (e.g. Aquic Paleboralfs) are named 'Aquic' or 'Oxyaquic' when soils are saturated with water, in one or more layers within 100 cm of the mineral soil surface, for 1 month or more per year in 6 or more out of 10 years (e.g. Oxyaquic Paleboralfs).

Alfisols which are shallow are classified as 'Lithic' (e.g. Lithic Cryoboralfs) and soils which show less pronounced characteristics of an Alfisol are classified as 'Inceptic' (e.g. Inceptic Fragixeralfs).

Alfisols with high base saturation are named 'Eutr' (e.g. Eutroboralfs, Eutric Glossocryalfs). If the base saturation (by sum of cations) is less than 75 % throughout the argillic horizon the prefix 'Ultic' is used for classification (e.g. Ultic Paleustalfs).

A special feature is the presence of lamellae, which are subhorizons (two or more), each with an overlying eluvial horizon. The lamellae layers are of pedogenic origin. Alfisols with these features are classified as 'Lamellic' (e.g. Lamellic Eutroboralfs). Alfisols which are relatively old soils showing pronounced characteristics to qualify for this order are denoted by 'Pale' (e.g. Paleustalfs).

Soil temperature regimes are used to classify Alfisols at the great group and subgroup level: 'Cryic' (e.g.), 'Xeric' (e.g. Xeric Palecryalfs), 'Ustic' (e.g.), 'Aridic' (e.g. Aridic Kandiustalfs), 'Udic' (Udic Paleustalfs), 'Torrertic' (e.g. Torrertic Natrustalfs).

12.1.5) Distinguishing Characteristics

If the Entisols are considered of soils in the stage of minimum organization the Alfisols show a higher degree of organization. Weathering and eluviation / illuviation altered Entisols or Inceptisols to form Alfisols. Transitions between areas of Alfisols and Spodosols lie in ecotones between mixed deciduous forest and coniferous forest. The Ustalfs tend to form a belt between the Aridisols of arid regions and the Udalfs, Ultisols, Oxisols, and Inceptisols of humid regions. A lower content of organic matter in the surface horizon distinguishs the Alfisols from the Mollisols, which develop under grassland or prairie. The soil moisture is not high enough to accumulate organic matter to form Histosols. A pergelic soil temperature regime would develop Gelisols. Other soil orders with argillic horizons are Ultisols, Mollisols, and Aridisols.

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12.2) Andisols

Summary:

- Vegetation: variety of vegetation types
- Climate: all soil temperature regimes, except pergelic
- Soil moisture regime: all soil moisture regimes
- Major soil property: andic soil properties (low bulk density, oxalate extractable aluminum and iron, short-range-order minerals compounds - amorphous material, high phosphate sorption capacity) related to volcanic origin of materials.
- Diagnostic horizons: cambic
- Epipedon: histic, melanic
- Major processes: weathering, humification, melanization, leaching, P-fixation

12.2.1) Environmental Conditions

- Climate: Andisols form in all soil moisture and all soil temperature regimes, except pergelic. Formation of Andisols in arid regions is limited because of slow weathering of volcanic parent materials.
- Vegetation: Andisols develop under a variety of vegetation types ranging from coniferous and deciduous forest, tundra, to shrubs.
- Relief: Andisols are found on any topography, however, often they occur on steep slopes formed by volcanic activity.
- Parent Material: The vast majority of Andisols formed from pyroclastic deposits (volcanic ejecta) such as ash, pumice, cinders, and lava. Volcanic terrains have a greater variety of rock-types than other surface environment on earth. These terrains include lavas, pyroclastic deposits (from explosions), and deposits from a wide range of sedimentary processes that occur in volcanic terrains. The nature of volcanic material ejected from a volcano varies greatly in time and space and determines the size of particles, composition of materials, and depth of volcanic material deposited. Rapid cooling of the molten materials upon ejection

prevents crystallization of minerals with long range atomic order, and the resulting product is vitric material or volcanic glass, which are dominated by amorphous, short-range-order minerals.

Time: Because volcanoclastic material is more weatherable than crystalline materials Andisols do not need very long time periods to form.

12.2.2) Processes

Volcanic ash is chemically/mineralogically distinct from most other soil parent materials. It is composed largely of vitric or glassy materials containing varying amounts of Al and Si. Volcanic glass lacks a well-defined crystal structure (i.e., amorphous) and is quite soluble. Environmental conditions, notably vegetation and soil moisture regime together with chemical composition (Al:Si ratio, base status, pH etc.) strongly influence weathering pathways of volcanic glass.

Allophane and imogolite are common early-stage residual weathering products of volcanic glass and both have poorly-ordered structures. Allophane forms inside glass fragments where Si concentration and pH are high and has a characteristic spherule shape. Imogolite tends to form on the exterior of glass fragments under conditions of lower pH and Si concentration, and has a characteristic thread-like morphology. Both allophane and imogolite may complex with organic matter. In some instances, where organic matter is rapidly accumulating, neither allophane or imogolite form in large amounts. Instead, opaline silica and Al-humus complexes are formed, which appear to inhibit allophane and imogolite formation.

Allophane, imogolite and humus complexes are generally transformed under leaching conditions. In Si-rich environments, halloysite formation is favored, under more basic conditions gibbsite is favored. In non-allophanic ashes 2:1 clays occur although their pathways of formation are not well-defined. Soil moisture regimes influence transformation rates - crystalline clay formation is favored under regimes that include dry seasons (e.g., ustic and drier) and moist regimes (udic) favor persistence of amorphous complexes.

The weathering products such as Al, Fe, and non-crystalline aluminosilicates stabilize humic substances and render them recalcitrant to decomposition, i.e., humic acids are accumulated (humification). Al, Fe-humus complexes are only sparingly soluble and therefore they accumulate at the surface, forming dark thick surface horizon especially under grass vegetation and humid climate (histic or melanic epipedons). The formation of Al, Fe-humus complexes is associated with a change in soil color (black color -organic matter), which is called melanization.

Leaching of base cations is associated with the free drainage of many Andisols, i.e., percolating water leaches the cations out of the soil.

A characteristic of Andisols is their tendency to fix phosphate in a plant-unavailable form. The highest P fixation is found in those Andisols that are fine textured and have relatively high Al/Si ratios. The phosphate is apparently bound by the aluminum via an anion exchange for hydroxyl.

12.2.3) Properties

Andisols are dominated by short-range-order compounds (e.g. allophane, imogolite), including organo-metallic complexes, ferrihydrite, and aluminosilicates, that formed largely in situ.

A typical soil profile show a thick, dark-colored, greasy mineral horizon (e.g. melanic epipedon), a weakly developed cambic subsurface horizon (Bw), and relatively unaltered volcanic or volcanoclastic parent material (C). Histic or melanic epipedons are common in Andisols. A melanic epipedon has to be 30-cm or thicker with a black color and a histic epipedon requires more than 12 % to 18 % organic carbon, depending on clay content. Typically, Fe-Al-humus complexes are found in the A horizon, whereas short-range-order minerals are found in the Bw horizon.

In general, the pH-functional cation exchange capacity (CEC) is high, due to a high surface area of the mineral and organic compounds in Andisols. The %-base saturation is often low because of high percolation and leaching of cations in many Andisols.

Physical soil properties of Andisols comprise a low bulk density, high macroporosity with rapid drainage at low soil moisture tensions, and weak mechanical strength. When they are dry Andisols are highly susceptible to wind erosion.

12.2.4) Classification

To qualify for an Andisol a soil have to have andic soil properties in 60 % or more of the thickness of soil material within 60 cm of the mineral soil surface, or on the top of an organic layer with andic properties. Andic soil materials contain less than 25 % organic carbon (by weight) and, in the fine-earth fraction (> 2 mm), meet one or both of the following:

- Al plus 1/2 Fe extractable % (by ammonium oxalate - amorphous phases) totals 2% or more

- A bulk density, measured at 33 kPa water of 0.9 g/cm^3 or less,

- Phosphate retention of 85% or more.

In cases where the particle size is composed of 30% or more particles in the 0.02 to 2.00 mm fraction, the limits listed above are modified to account for less of an active amorphous component in the soil and thus lower limits on P-adsorption and amounts of amorphous Al/Fe.

There are 7 different suborders in the Andisol order distinguished by soil moisture regime, water holding capacity, or organic matter content:

- Aquands: Aquands are Andisols that have a histic epipedon or have aquic conditions which result in redoximorphic features.

Aquands occur locally in depressions and along floodplains where water tables are at or near the soil surface for at least part of the year.

Cryands: They are defined as Andisols with cryic soil temperature regimes. These soils are the Andisols of high latitude (e.g. Alaska, Kamchatka) and high altitude (e.g. Sierra Nevada in the U.S.).

Torrands: They are defined as Andisols with aridic soil moisture regimes. Vegetation is mostly desert shrubs.

Xerands: They are defined as Andisols with xeric soil moisture regimes.

Vitrands: They are Andisols that have a low water-holding capacity. Vitrands are restricted to ustic and udic soil moisture regimes.

Ustands: They are defined as Andisols with ustic soil moisture regimes. These are the Andisols of the intertropical regions that experience seasonal precipitation distribution.

Udants: They are defined as Andisols with udic soil moisture regimes (most extensive Andisols).

Shallow Andisols that have a lithic contact within 50 cm either of the mineral soil surface, or of the top of an organic layer with andic soil properties, whichever is shallower are denoted 'Lithic' (e.g. Lithic Cryaquands, Lithic Haploxerands).

Andisols with very low base status (that have extractable bases plus KCl-extractable Al3+ totaling less than 2.0 cmol(+)/kg in the fine-earth fraction) are named 'Acrudoxic' (e.g. Acrudoxic Placudands), low base status soils that have more than 2.0 cmol(+)/kg Al3+ (by KCl) in the fine-earth fraction are named 'Alic' (e.g. Alic Epiaquands), and Andisols that have extractable bases plus KCl-extractable Al3+ totaling less than 15.0 cmol(+)/kg are labeled 'Dystric' (e.g. Dystric Haplustand), whereas Andisols with high base status (that have a sum of extractable bases of more than 25.0 cmol(+)/kg in the fine-earth fraction) are named 'Eutric' (e.g. Eutric Placudands).

Soil moisture regime is used to distinguish Andisols at the great group and subgroup level: xeric (e.g. Xeric Vitricryands), ustic (e.g. Ustivitrands), udic (e.g. Udivitrands), aquic (e.g. Aquic Ustivitrands), and 'oxyaquic', i.e., soils that are saturated with water, in one or more layers within 100 cm of the mineral soil surface, for 1 month or more per year in 6 or more out of 10 years (e.g. Oxyaquic Vitricryands). Andisols with episaturation, i.e., the soil is saturated with water in one or more layers within 200 cm of the mineral soil surface and also has one or more unsaturated layers with an upper boundary above 200 cm depth, below the saturated layer(s) (a perched water table) are denoted by 'Epi' (e.g. Epiaquands).

Epipedons are used to classify 'Melanic' and 'Histic' Andisols (e.g. Melanaquands, Histic Cryaquands). Andisols, which show a layer 10 cm or more thick with characteristics of a mollic epipedon and more than 3 % organic carbon are named 'Thaptic' (e.g. Thaptic Cryaquands). Andisols, which have more than 6.0 percent organic carbon and colors of a mollic epipedon throughout a layer 50 cm or more thick within 60 cm either of the mineral soil surface, or of the top of an organic layer with andic soil properties, whichever is shallower are named 'Pachic' (e.g. Pachic Melanoxerands). Generally, Pachic is term to identify a thickened mollic epipedon.

Water retention characteristics are used to classify Andisols at the great group and subgroup level. Andisols that have a 1500-kPa water retention of less than 15 % on air-dried samples and of less than 30 % on undried samples dominant in the upper 60 cm are named 'Vitric' (e.g. Vitraquands, Vitric Haplocryands). Andisols that have, undried, a 1500-kPa water retention of 70 % or more throughout a layer 35 cm or more thick within 100 cm either of the mineral soil surface, or of the top of an organic layer with andic soil properties, whichever is shallower are named 'Hydric' (e.g. Hydrocryands, Hydric Melanaquands).

Diagnostic horizons are used to classify 'Petrocalcic', i.e., an indurated calcic horizon (e.g. Petrocalcic Vitritorrands), 'Calcic', i.e., a horizon with secondary accumulation of carbonates (e.g. Calcic Vitritorrands), 'Alfic', i.e., the presence of an argillic or kandic horizon (e.g. Alfic Vitrixerands), 'Ultic', i.e., the presence of an argillic or kandic horizon plus a base saturation (by sum of cations) of less than 35 percent throughout its upper 50 cm (e.g. Ultic Haploxerands), 'Oxic', i.e., an horizon with sandy loam or finer and a high content of low-charge 1:1 clays (e.g. Oxic Haplustands), 'Placic', i.e., a 2 to 10-mm thick dark reddish brown to black iron or manganese pan (e.g. Placaquands), or presence of a duripan, i.e., a horizon cemented by illuvial silica (e.g. Duric Placaquands).

12.25) Distinguishing Characteristics

The geographic distribution of Andisols is closely related to volcanoes that are active or have been active during the Holocene. Soils formed on older volcanic deposits are dominated by crystalline aluminosilicates or the material is mixed with other parent material, therefore, the criteria to qualify for Andisols are not given. Andisols are limited to soils formed on volcanic materials that have weathered enough to produce short-range-order organo-metallic and aluminosilicate compounds, but that have not weathered to the point where crystalline materials predominate or where significant transformations has occured.

Soils from a variety of soil orders may be found on volcanic terrains, but Andisols are almost exclusively confined to the pyroclastic materials. Soils developed in pyroclastic and other fragmental volcanic materials occupy only about 0.8% of the earth's surface. However, because of their very distinct characteristics, they are recognized as a separate soil order in soil taxonomy.

Most Andisols are formed from specific parent material (volcanic ejecta). Few soil orders, except Histosols, have such a specific range of parent materials and depositional environments.

The separation between Spodosols and Andisols is difficult, because short-range order aluminosilicates and organo-metallic complexes occur in the B horizons of soils of both orders. A distinguishing characteristic is the transformations in situ and lack of intensive illuviation of these compounds in Andisols.

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12.3.1) Aridisols

Summary:

- Vegetation: Present vegetation - species adapted to arid climate; former vegetation - not specified
- Climate: Arid regions (cold and warm deserts); cryid or frigid - thermic or hypothermic soil temperature regime
- Soil moisture regime: aridic, torric
- Major soil property: crusts, desert pavement, accumulation of material such as clay, $CaCO_3$, or salts
- Diagnostic horizons: cambic, argillic, calcic, petrocalcic, natric, gypsic, petrogypsic, salic
- Epipedon: ochric, anthropic
- Major processes: weathering, silication, calcification, hardening, salinization, solodization, deflation

12.3.1) Environmental Conditions

Climate: Arid regions including cold polar, cool temperate and warm deserts, which occupy about 36% of the land surface based on climate and about 35% based on vegetation. Aridisols may also occur in semi-arid areas outside of zones broadly classified as arid - e.g. where local conditions impose aridity - steep, south-facing slopes in N-hemisphere, physical properties that limit water infiltration. Aridisols are classified on the basis of their soil moisture regime (more specifically referenced to the soil moisture control section), which is dry in all parts >50% of the time in most years, and not moist for as much as 90 consecutive days when the soil is warm enough (>80C) for plant growth. In an aridic (&torric) soil moisture regime, potential evapotranspiration greatly exceeds precipitation during most of the year. In most years, little or no water percolates through the soil. This hydrologic regime has a distinctive influence on the development of such soils. During Quarternary time, most deserts have changed back and forth from cooler-moister, to warmer-more-arid climates, therefore, change in climatic conditions have to be considered when talking about Aridisols.

Vegetation: Present vegetation comprises species adapted to dry climate such as cactus (Cactaceae), mesquite (Prosopis), creosotebush (Larrea), Yucca (Yucca), sagebrush (Artemisia), or shadscale (Atirplex). Species have to live in an environment with sparse organic matter, low microbial population, and lack of nutrients such as nitrogen and phosphorous. Use of Aridisols is limited because of lack of water, low biotic activity and low nutrient status. Irrigation can be used to improve crop growth on Aridisols, but issues of internal permeability, salinization and alkalization arising from the irrigation water should be addressed.

Relief: They form on plain terraces and on steep slopes

Parent Material: They occur on land surfaces of Pleistocene or greater age, therefore, they occur on parent material such as crystalline rocks. Aridisols do develop on fluvial and eolian materials, extensively in large deserts such as the Gobi, Namib, or Kalahari desert. Aridisols occur on gypsiferous material formed from marine sedimentary rocks, on unconsolidated sediments, or

Kalahari desert. Aridisols occur on gypsiferous material formed from marine sedimentary rocks, on unconsolidated sediments, or limestone.

Time: Most Arisisols are found on landscapes that are relatively old and stable (up to more than million years).

12.3.2) Processes

In arid regions chemical and physical reactions operate in the same way as in humid regions, although with less intensity and at shallower depths. Physical weathering such as weathering due to the crystallization of salts or thermal expansion and contraction of the constituents minerals is favored in arid regions. Chemical weathering is retarded because of lack in water although the importance of chemical weathering has been proved in many pedological research studies.

Because of sparse vegetation and low humification rates little humus accumulates in the typic Aridisol, i.e., in many Soils ochric epipedons are found.

Evidence of leaching below the average depth of water storage is commonly observed in Aridisols and is explained by: (i) more humid paleoclimates, and/or (ii) the influence of occasional, exceptionally large precipitation events.

Examination of soil forming processes in arid zones invariably requires consideration of possible paleoclimatic influences (i.e. some features in the soil may have formed under conditions quite different from those operating at present), the periodic occurrence of large precipitation events that can punctuate the otherwise dry environment of these regions and local variation in factors that prescribe soil genesis. It seems to be contradictory that horizons accumulated with clay, sodium, salts, gypsum, or silica occurs in Aridisols which is associated with illuviation of those materials. A prerequisite for leaching or eluviation/illuviation is rainfall. Aridisols occur on landscapes that are more than one million years old, a time scale that has allowed for development of accumulations of clay, carbonates, and silica.

A predominant influence on soil formation in arid zones is that potential evapotranspiration greatly exceeds precipitation during most of the year. Thus, drainage of water through the soil is limited. The occurrence of horizons enriched in secondary minerals is strongly controlled by the distinct hydrology of arid regions which favors limited leaching from the solum. The source of secondary enrichment may be atmospheric, from groundwater and weathering of soil minerals. Thus, in evaluating the occurrence and significance of enrichment it is important to evaluate mineral source(s), hydrology and relative age of the soil-landscape. Relative age is important because many of the processes of enrichment are necessarily time dependent. The processes associated with the accumulation of materials in Aridisols are: (i) lessivage or eluviation/illuviation of clays - argillic horizons, (ii) silication, i.e., the accumulation of silica - duripans, (iii) calcification, i.e., the accumulation of $CaCO_3$ - calcic or petrocalcic horizons. The hardening of soil material may lead to a decrease in volume of voids by infilling with salts and silica. This process is responsible for the formation of petrocalcic, petrogypsic horizons or duripans.

The composition of the initial material in which some Aridisols are forming that contain argillic, natric and calcic horizons does not readily explain their internal enrichment in phyllosilicate clays or carbonates. Thus, it has been suggested that aeolian inputs may explain this enrichment. However, in some settings subsurface water enriched with clays and especially carbonates may also account for formation of Bt, Btn and Bk(m) horizons.

account for formation of Bt, Btn and Bk(m) horizons.

Soluble salt accumulation (salinization) is usually associated with depressional landscape positions, such as playas, and a source of saline ground water. Saline accumulations such as sulfates and chlorites of Ca, Mg, K, and Na are also associated with some irrigated agricultural areas. The accumulation of Na salts is called solodization. The accumulation of salts is often associated with a natural or artificially high water table (irrigation) feeding capillary water to, or near to the soil surface where salt accumulates upon evaporation. Salinization of irrigated agricultural areas in semi-arid and arid areas is a problem that has plagued the human race since the dawn of 'civilization'.

Rubification, i.e, the reddening of the soil due to oxidation of Fe-bearing minerals is often observed in Aridisols. Soil moisture conditions in arid regions favors oxidation over redoxidation.

The processes deflation and deposition are responsible for the development of 'desert pavement' (surface pebble layers). Deflation is the sorting out, lifting, and removal of loose, dry, fine grained soil particles by the turbulent action of the wind. It is assumed that vertical sorting of stones, i.e., the gradual upward migration of pebbles that have been heaved up by swelling clay, with local supplement action by frost, growth of salt crystalls, and expansion of entrapped air, with preferential collapse of fines into voids too small to accept pebbles during subsequent desiccation support developing a surface pebble layer. The pavement serves as a dust trap but inhibits loss of soil particles by wind erosion.

12.3.3) Properties

Pedogenic processes produced numerous soil features associated with dry climate: (i) crusts, (ii) desert pavement, (iii) cambic horizons, (iv) argillic horizons, (v) natric horizons, (vi) carbonate accumulations (calcic and petrocalcic horizons), (vii) duripans, (viii) salic and gypsic horizons.

(i) Crusts are surficial layers generally less than 10- to 20-cm thick. They are dominated by fine material composed of compound polygonally prismatic and platy fragments that are coherent when dry. When silt particles dominate they may exhibit vesicular porosity. The distinctive morphology of crusts probably results from repeated wetting and drying, entrapped air during wetting likely accounts for vesicle formation. The impact of soil crusts to infiltration is high, because crusts slow the permeability to water in contrast to rapid infiltration that happens in uncrusted soils.

(ii) Desert pavement is a surface pebble layer. Several pathways, which probably operate over tens of thousands of years may account for the same end product, these include: (a) removal of fine particles from surface by wind/water, leaving a 'lag' of coarser fragments, (b) vertical sorting of coarse fragments towards surface via wet/dry, freeze/thaw, and uplift by swelling clay, salt growth, air entrapment below, concomitant downward movement of fines, and (c) over time, pavement becomes 'flat' and covered with a thin veneer of 'varnish', composed of Fe, Mn and silicate clays, microbiological processes may contribute to its formation in some settings.

(iii) Cambic horizons (Bw) have a texture of loamy very fine sand or finer and contain some weatherable minerals. They are characterized by the alteration or removal of mineral material as indicated by mottling or gray colors, stronger chromas or redder hues than in underlying horizons. Carbonates are leached out in low-carbonate parent material, whereas in highly calcareous hues than in underlying horizons. Carbonates are leached out in low-carbonate parent material, whereas in highly calcareous parent materials, evidence of carbonate removal may take the form of carbonate coatings on undersides of pebbles in the cambic horizon.

(iv) Argillic horizons (horizons enriched in clay - Bt) may form due to in situ weathering or illuviation of clay in the Bt horizon. Carbonates have to be leached before illuvial clay can accumulate in argillic horizons because clay flocculates in the presence of carbonates.

(v) Natric horizons (n in combination with any master horizon) satisfy the requirements of an argillic horizon, but also has prismatic, columnar, or blocky structure, and > 15 % saturation with exchangeable Na^+. Sodium has characteristic effects of soil physical properties. In the presence of Na clay and humus disperse into individual hydrated particles instead of remaining flocculated. Sodic soils readily lose their structure, deflocculation occurs, the soil structure is destroyed, and pores clog at the surface, therefore the permeability at the surface is reduced.

(vi) Calcic and petrocalcic horizons (Bk and Bkm or Ck and Ckm) show an accumulation of carbonate and they commonly lie below argillic and cambic horizons in Aridisols. Generally, carbonates are leached out before clay are translocated to form an argillic horizon. Calcic horizons develop over time into petrocalcic horizons, which are indurated calcic horizons cemented by calcium carbonate and in some places with magnesium carbonate. Petrocalcic horizons cannot be penetrated with a spade or auger when dry and the cemented layer is impenetrable to roots.

(vii) Duripans (Bqm or Cqm) are subsurface soil horizons cemented by illuvial silica, usually opal or microcrystalline forms, to the degree that less than 50 % of the volume of air-dry fragments will slake in water or HCl. Often the duripans in Aridisols have a considerable content of calcium carbonate and can be distinguished only by the test described above.

(viii) Salic horizons (Bz or Cz) are enriched with secondary salts more soluble than gypsum. A salic horizon is 15 cm or more in thickness and contains at least 20 g/kg salt. A gypsic horizon (By or Cy) is enriched of secondary $CaSO_4$, is > 15 cm thick, and has at least 50 g/kg more gypsum than the C horizon. High pH values (> 9) are associated with nutrient deficiencies or toxicities induced by high pH. Calcium is immobilized because high pH promotes the formation of carbonate from CO_2, and carbonated precipitates with Ca, as $CaCO_3$. A high pH also affects the sorption behavior of these cations in the soil.

Most Aridisols show a low permeability because of the presence of accumulated or cemented layers. The nutrient status of often low, however, supplies of micronutrients are usually abundant, although they may not be available because of the high pH.

12.3.4) Classification

An criterion of salinity is the electrical conductivity (EC) of the saturation extract. Soils are considered saline if their EC exceeds 4 dS/m. Usefuls measures of sodicity are the exchangeable sodium percentage (ESP) and the sodium adsorption ratio (SAR). The ESP is the exchangeable Na expressed as a percentage of the total exchangeable cations. The SAR is a modified ratio of Na to other major cations (Ca and Mg) in the saturation extract.

ESP = 100 (exch. Na) / (exch. Na + exch. Ca + exch. Mg)

(the cation amounts are expressed in mols of charge (gram equivalents).

SAR = (Na) / Wurzel (Ca * Mg) /2

(the cations are expressed in mols of charge (gram equivalents) per liter.

Three classes of salt-affected soils are recognized and defined in terms of electrical conductivity and exchangeable sodium percentage:

- Saline: Has a saturation extract conductivity of 4 mmhos/cm or greater and has a low exchangeable sodium percentage.
- Sodic: Has an exchangeable sodium percentage of 15% or greater but has a low salt content.
- Saline-sodic: Has both the salt concentration to qualify as saline and sufficient exchangeable sodium to qualify as sodic.

The requirements to classify for an Aridisol are:

- an aridic soil moisture regime
- an ochric or anthropic epipedon, and
- one or more of the following subsurface horizons within 100 cm of the soil surface: argillic, cambic, natric, salic, gypsic, petrogypsic, calcic, petrocalcic, or duripan.

The Aridisols are composed of 7 suborders distinguished by (i) soil temperature regime, and (c) occurrence of particular diagnostic horizons:

- Cryids: Cryic soil temperature regime, MAT higher than 0°C but less than 8°C.
- Salids: Salic horizon that has its upper boundary within 100 cm of the surface.
- Durids: Duripan that has its upper boundary within 100 cm of the surface.
- Gypsids: Gypsic of petrogypsic horizon that has its upper boundary within 100 cm of the surface and lacks an overlying

Gypsids: Gypsic or petrogypsic horizon that has its upper boundary within 100 cm of the surface and lacks an overlying petrocalcic horizon.

Argids: Argillic or natric horizon that has its upper boundary and does not have petrocalcic horizon within 100 cm of the surface.

Calcids: Calcic or petrocalcic horizon that has its upper boundary within 100 cm of the surface.

Cambids: Other Aridisols

<description of great groups and subgroups is under construction >

12.3.5) Distinguishing Characteristics

Soils with a dominance of attributes not specifically associated with arid-zone soil forming processes are assigned to other pertinent Orders even though their hydrologic regime is the same as that used for Aridisols. In such instances, the prefix 'Torr' or 'Torri' is used to identify these soils. This prefix refers to the Torric soil moisture regime which is identical to the Aridic soil moisture regime and is defined as:

- Dry in all parts more than half the time that the soil temperature at a depth of 50 cm is above 5°C

- Never moist in some or all parts for as long as 90 consecutive days when the soil temperature at a depth of 50 cm is at or above 8°C

Other soil orders such as the Entisols and Mollisols use the prefixes 'Torric', 'Ustic', and 'Xeric' to classify soils developed in regions with dry climate. Many Aridisols are closely associated with the occurence of Entisols.

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12.4.1) Entisols

Summary:

- Vegetation: not specified, bare soil
- Climate: pergelic to hypothermic
- Soil moisture regime: dry to aquic
- Major soil property: featureless soil bodies
- Diagnostic horizons: typically absent, albic
- Epipedon: ochric
- Characteristic: little or no evidence of soil development

12.4.1) Environmental Conditions

➤Climate: Entisols may form in a variety of climates. For example, an arid or pergelic climate may limit the amount of soil development to inhibit the formation of other soil orders. A pronounced saturation of the soil profile or even submergence for long enough periods inhibit soil development and soils persist in the Entisol order.

➤Vegetation: Harsh environments may limit root and plant growth due to consolidated highly resistant bedrock, infertility or toxicity of initial material, submergence, or high erosion rates. When adequately fertilized and their water supply is controlled some Entisols can be used in agriculture (rangeland, grazing land). However, restrictions on their depth, clay content, or water balance limit intensive use of large areas of these soils. Some Entisols are intensively farmed, for example, river alluvium Entisols.

➤Relief: Entisols may be present on very steep slopes on hard bedrock where soil formation is inhibited. Mass movement may remove material from such an area as fast or faster than most pedogenic horizons form. Other Entisols form on level to gently sloping relief in deposited material such as alluvium or colluvium.

➤Parent Material: Entisols are on land surfaces that are very young (alluvium, colluvium, mudflows), extremely hard rocks (e.g. Orthents), or disturbed material (e.g. mined land, highly compacted soils, toxic material). They also occur on deep bodies of water and glaciers which are transitions between 'soils' and 'not soils'. Psamments are Entisols formed in sandy material and are found in Alabama and Georgia and used mostly for grazing. They are also typical of the shifting sands of the Sahara Desert and Saudi Arabia. In serpentine barrens, Entisols may be associated with bedrock outcrops. Entisols may be also associated with salt flats.

➤Time: Shortness of time since exposure of initial materials to the active factors of soil formation limits soil development. Fresh lava flows, marine or lacustrine deposits newly exposed by uplift of land or by lake drainage, provide sites for very young soils. Human activity may force the formation of Entisols. Deforestation may induce soil erosion where highly eroded, shallow Entisols remain. For example, wide areas are formed due to deforestation and erosion in southern Europe and in Southern America.

12.4.2) Processes

The characteristic of Entisols is that there is little or no evidence of soil development. They form a transition between the other soil orders of Soil Taxonomy and non-soil material such as bare rock, deep water or ice at the surface of the earth. In chapter 15.1.1. the environmental conditions for Entisols were described which often inhibit soil formation, i.e., some factors slow down soil forming processes. For example, submerged or waterlogged soils exclude oxidation and retard weathering. Sparse vegetation results in low litter amounts which retards the accumulation of organic matter in the topsoil. The high compactness of rock may inhibit the penetration of roots and therefore inhibit plant growth.

The impact of most soil forming processes is not great enough to produce soil features recognized as diagnostic for other soil orders. Entisols may be 'climax soils' which are in equilibrium with the environment, they may form by soil degradation (e.g. soil erosion) from other soil orders, or they may develop from 'non-soil areas'.

12.4.3) Properties

Entisols are soils without properties that are diagnostic of the other orders. Besides an ochric epipedon and an albic diagnostic horizon they may have some fragments of diagnostic horizons that are not arranged in any discernible order.

12.4.4) Classification

In the Entisols order there are 5 suborders:

- Aquents: Entisols which are permanently or seasonally wet (saturated) are mapped as Aquents. They show pronounced redoximorphic features.

- Arents: They are better drained than Aquents (lacking their redoximorphic features) and exhibit fragments of diagnostic horizons below the Ap horizon. Arents are deeply disturbed by farming, mining, or construction.

- Psamments: The soil texture of Psamments is loamy fine sand or coarser. They are subject to movement by wind if dry.

- Fluvents: The soil texture of Fluvents is loamy and clayey (finer in texture than loamy fine sand). They are found on stratified alluvial material.

- Orthents: The soil texture of Orthents is loamy and clayey. They are better drained than Aquents with a regular decrease in content of organic matter with depth.

The suborders are subdivided into great groups on the basis of several factors: mean annual soil temperature and range of soil temperature, content of sand and quartz, stratification, presence of sulfidic material, and low-bearing capacity.

Hydraquents are formed in sediments that have accumulated under water and remained continously submerged. To qualify for a Hydraquent the n-value must be > 0.7. The n-values is used to define the grams of water associated with 1 gram of clay and obtained from the relationship:

$$A = nL + nbH + pR$$

where

A: water content per 100 g of dry soil

L: clay percentage

H: organic matter percentage

R: non-clay content

b: ratio of water retention by organic matter to clay (commonly taken as 3)

p: water associated with the non-clay (commonly 0.2)

In many subgroups of the Entisol order soils with aquic conditions some time in most years, redox depletions with a chroma of 2 or less are considered (e.g. Aquic Cryopsamments). In other Entisols that are saturated with water, in one or more layers within 100 cm of the mineral soil surface, for 1 month or more per year in 6 or more out of 10 years the term 'oxyaquic' is used (e.g. Oxyaquic Cryopsamments). Influence of soil temperature is considered on great group and subgroup level using designations such as ustic, xeric, torri, or udic.

Accumulation of iron sulfides (FeS_2) are found in lagoonal soils or distrubed soils in coal mine spoil. They are classified on great group level (e.g. Sulfquents) and subgroup level (e.g. Sulfic Hydraquents, Sulfic Fluvaquents). Some Entisols show mollic characteristics (e.g Mollic Cryofluvents, Mollic Ustifluvents).

Shallow soils with a lithic contact within 50 cm of the soil surface are common in the Entisol order (e.g. Lithic Cryopsamments, Lithic Quarzipsamments, Lithic Xerorthents).

Soils which show a fine-earth fraction containing 30 percent or more particles 0.02 to 2.0 mm in diameter of which 5 percent or more is volcanic glass, and [(Al plus 1/2 Fe, percent extracted by ammonium oxalate) times 60] plus the volcanic glass (percent) is 30 or more throughout one or more horizons with a total thickness of 18 cm or more within 75 cm of the mineral soil surface, are grouped as 'vitrandic' (e.g. Vitrandic Xerofluvents, Vitrandic Cryorthents). Entisols that have, throughout one or more horizons with a total thickness of 18 cm or more within 75 cm of the mineral soil surface, a fine-earth fraction with both a bulk density of 1.0 g/cm^3 or less, measured at 33 kPa water retention, and aluminum plus 1/2 iron percentages (by ammonium oxalate) totaling more than 1.0 are grouped as 'andic' (e.g. Andic Cryofluvents).

12.4.5) Distinguishing Characteristics

Entisols are transitions between the other soil orders and non-soils. Non-soils are very unstable areas either because of water erosion (e.g. badlands, beaches, riverwash), wind erosion (e.g. dunes), areas impenetrable to roots (e.g. rock outcrops), areas that restrict plant growth (e.g. salt flats, slickens, toxic areas), or areas that are too cold to support plant growth. Many young soils are excluded from Entisols because presence of a mollic epipedon. Because cambic horizons cannot occur in soil materials coarser than very fine sand weathered sandy soils are grouped in the Entisol order.

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12.5.1) Gelisols

Summary:

- Vegetation: lichens, moss, liverwort, sedges, grass
- Climate: pergelic
- Soil moisture regime: variety of soil moisture regimes
- Major soil property: accumulation of organic matter, special features formed by cryoturbation
- Diagnostic horizons: -
- Epipedon: histic
- Major processes: cryoturbation
- Characteristics: soils that contain within 200 cm of the ground surface permafrost (permanently frozen ground)

12.5.1) Environmental Conditions

➤Climate: Gelisols develop in climatic regions where temperatures continuously are at or below 0° C (e.g. alpine, polar regions) - pergelic temperature regime. They occur in arid regions and areas with effective precipitation. Permafrost (i.e., permanently frozen soil) is a characteristic environmental factor for the development of Gelisols. The distribution of permafrost comprise two zones: (i) continuous permafrost: the zone at the highest latitudes and elevations where permafrost is ubiquitous; the southern boundary corresponds to the -7 °C isotherm. (ii) discontinuous (sporadic) permafrost: the zone in which permafrost occurs only in some materials; the southern boundary corresponds to the 0 to -2 °C isotherm.

➤Vegetation: Cold climate inhibits the growth of many species; only species adapted to harsh cold environmental conditions can survive, for example, lichens, sphagnum moss, liverwort, sedges, grass, Picea Betula, Salix.

➤Relief: There is no limitation in relief for the formation of Gelisols.

➤Parent Material: Gelisols can form in any parent material. Often they form in glacial drift material.

➤Time: At very low temperatures (< 0 to -70° C) pedogenic processes are slowed down, i.e., soil development is very slow. Many soils in cold regions are very old, e.g. in Antarctica millions of years.

12.5.2) Processes

Definition of Permafrost (permanently frozen soil): A condition existing below the ground surface, irrespective of texture, water content, or geologic character, in which the temperature of the material remained below 0 °C continuously for two or more years. The soil above the permafrost that thaws in the summer is referred to as the 'active layer'.

Cryopedogenesis is the sum of all subprocesses occuring in cryogenic soils, including compaction (desiccation), displacement (alignment, rotation, sorting, inclusions), and pore formation.

Cryoturbation (frost churning), which is mixing of soil due to freezing and thawing, results in the disruption of horizons, displacemetn of soil material, the incorporation of organic matter into lower horizons, and the orientation of stones in the soil profile. Cryoturbation in the soil profile is manifested by irregular and broken horizons and textural bands, involutions, organic matter accumulation on the permafrost table, oriented stones, silt caps and accumulations, and deformed soil material associated with movements due to ice- and sand-wedge growth.

At 0 °C, the increase in volume with the conversion from water to ice is 9 percent. When the moisture contained in rocks freezes, and the accompanying internal pressures are sufficiently great to exceed the strength of the rock, the rock ruptures (thermal cracking). Freezing, associated with an expansion of soil water, and thawing, associated with a contraction or collapse of soil layers, result in a new terrain called hilly thermokarst.

Frost cracking of ground into polygons results from shrinkage of the ground during cold dry winters. Water from the active layer in summer seeps into cracks and freezes, starting the growth of vertical ice wedges. With the approach of winter, refreezing of the moist soil may be by simultaneous, slow upward extension of cementing ice above the permafrost table and downward extension of surface freezing ground. Subsoil between these two approaching freezing fronts develops a massive condition from centuries of this seasonal compaction.

Patterned ground formation is a process which results in special features such as circles of stones, nets, polygons, steps, or stripes.

During summer periods the upper few centimeters or several decimeters of a pedon thaws. On slopes (> 1 % gradient) the upper soil layer, which is highly saturated with meltwater flows above the upper surface of the permafrost, called permafrost table. This process is called solifluction. Within solifluction layers stones are transported downhills to depression areas.

At low temperatures, particles of snow are as hard as grains of bedrock and can 'sandblast' ventifacts (wind erosion).

Pedogenic processes in very cold environments such as weathering, transformations and translocations of mineral and organic materials are slow. Because decomposition is retarded in cold climate and organic matter is accumulated and histic epipedons are formed.

12.5.3) Properties

The dark black epipedon in many Gelisols is classified as histic, which is formed by low decomposition rates.

Freezing and thawing in the zone above the permafrost table forms features such as unsorted and sorted circles of stones, nets, polygons, steps, stripes, mounds, pingos, peat rings, and beaded drainage patterns. Freezing and thawing forms platy and vesicular structures in surface mineral horizons, and blocky, prismatic, and massive structures in subsoil. Ice lenses may form close to the permafrost table.

Because pedogenic processes are retarded in cold regions the soil landscapes with Gelisols are fragile. It takes very long time periods to wipe out the impact of disturbances, for example, produced by human activity such as extracting geologic materials or digging of soil pits.

12.5.4) Classification

Gelisols occur in arctic regions such as Antarctica, Russia, Canada, Alaska. An estimated 13.4 % (18 million km^2) of soils of the planet are occupied by permafrost. The basic requirement to form Gelisols is:

- the presence of permafrost within 100 cm of the soil surface; or

- gelic materials within 100 cm of the soil surface and permafrost within 200 cm of the soil surface.

Gelic materials are mineral or organic materials that have evidence of cryoturbation and/or ice segregation in the active layer

Gelic materials are mineral or organic materials that have evidence of cryoturbation and/or ice segregation in the active layer (seasonal thaw layer) and/or upper part of the permafrost.

New soil horizon symbols are:

jj: cryoturbation

ff: dry permafrost

Wfm: glacic horizon (> 75 % ground ice in a layer >= 30 cm thick)

There are three different suborders of Gelisols:

Histels: Histels are organic soils similar to Histosols exept that they have permafrost within 2 meters below ground surface. They have 80 % or more organic materials from the soil surface to a depth of 50 cm or to a glacic layer or densic, lithic, or paralithic contact, whichever is shallowest. These soils occur predominantely in Subarctic and Low Arctic regions of continuous or widespread permafrost. Less than one-third of the active layer (the soil between the ground surface and a permafrost table) or an ice layer which is at least 30-cm thick has been cryoturbated.

Turbels: Turbels are soils that show marked influence of cryoturbation (more than one-third of the active-layer portion of the pedon) such as irregular, broken, or distorted horizon boundaries and involutions and areas with patterned ground. They commonly contain tongues of mineral and organic horizons, organic and mineral intrusions and oriented rock fragments. Organic matter is accumulated on top of the permafrost and ice wedges are a common features in Turbels. These soils occur primarily in the zone of continuous permafrost.

Orthels: Orthels are soils that show little or no cryoturbation (less than one-third of the pedon). Patterned ground (except for polygons) generally is lacking. These soils occur primarily within the zone of discontinuous permafrost, in alpine areas where precipitation is greater than 1400 mm per year.

The decomposition stage of organic material (fiber in the OM) distinguishs Gelisols on the great group and subgroup level. 'Fibric' (e.g. Fibristels), 'Hemic' (e.g. Hemistels), and 'Sapric' (e.g. Sapristels) organic material is considered to distinguis Gelisols at the great group level. 'Sphagnic' indicates the presence of sphagnum moss which influences soil development. In 'Humic' Gelisols a mollic, umbric, or histic epipedon is present (e.g. Humiturbels), in 'Umbric' Gelisols there is an umbric epipedon (e.g. Umbriorthels), and in 'Mollic' Gelisols show a mollic epipedon (e.g. Molliorthels).

'Glacic' (> 75 % ground ice in a layer >= 30 cm thick) is used at great group and subgroup level to classify Gelisols (e.g. Glacic Folistels, Glacic Aquaturbels).

The presence of calcium sulfate defines 'Gypsic' Gelisols (e.g. Gypsic Anhyturbels), soluble salts define 'Salic' Gelisols (e.g. Salic Anhyturbels), carbonates defines 'Calcic' Gelisols (e.g. Calcic Anhyturbels).

Gelisols with an argillic diagnostic horizon (e.g. Argiorthels) or a spodic horizon (Spodic Psammiorthels) are also considered in the classification of Gelisols.

Gelisols developed in sandy parent material are designated by the term 'Psammentic' (e.g. Psammentic Aquorthels, Psammiturbels).

'Sulfuric' Gelisols show a mineral or organic horizon that has a pH < 3.5, inhibits growth of plant roots, and has yellow mottles of jarosite (e.g. Sulfuric Aquaturbels).

There are two general types of permafrost: (i) dry permafrost, which contains insufficient interstitial water to cement the soil matrix, and (ii) wet frozen or ice-cemented permafrost, which contains sufficient moisture to cement the soil matrix. Gelisols formed in dry permafrost regions are classified as 'Anhy' (e.g. Anhyturbels, Anhyorthels). The denotion 'Foli' is used to classify Gelisols which are saturated with water only a few days each year (e.g. Folistels). Gelisols, which are saturated seasonally are classified as 'Aquic' (e.g. Aquistatels, Aquic Umbriorthels).

Gelisols formed in volcanic material (e.g. volcanic glass) which does not meet the criteria of the Andisol order are considered by the formative element 'vitrandic' (e.g. Vitrandic Molliorthels) or 'andic' if the fine-earth fraction exhibits a bulk density of 1.0 g/cm^3 or less (e.g. Andic Andic Molliorthels).

Soil depth distinguishs between 'Lithic' - shallow (e.g. Lithic Anhyorthels) and 'Cumulic' - accumulated (e.g. Cumulic Umbriorthels) Gelisols. Gelisols, which have a mineral layer 30 cm or more thick that has its upper boundary within the control section below the surface tier are classified as 'Terric' (e.g. Terric Sapristels).

12.5.5) Distinguishing Characteristics

In the past, Soil Taxonomy has identified Gelisols as pergelic subgroups of Entisols, Inceptisols, Histosols, Mollisols, and Spodosols.

Gelisols and Histosols show high organic matter contents, whereas Gelisols are limited to cold climate.

Further Reading

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12.6) Histosols

<under construction>

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12.7) Inceptisols

Summary:

- Vegetation: not specified
- Climate: variety of climates excluding arid
- Soil moisture regime: variety of soil moisture regimes except aridic
- Major soil property: few diagnostic features
- Diagnostic horizons: cambic but no spodic, argillic, kandic, natric, and oxic horizon
- Epipedon: ochric, umbric, histic, or plaggen (mollic)
- Major processes: mass movement, soil erosion, deposition
- Characteristics: Environmental conditions inhibit soil-forming processes

12.7.1) Environmental Conditions

Climate: Inceptisols form under a variety of climates except aridic conditions. Soil moisture regimes can be variable ranging from poorly drained soils to well-drained soils on steep slopes. By definition, Inceptisols cannot have an aridic soil moisture regime. Climate which inhibits soil development such as low temperatures or low precipitation favors the development of Inceptisols. The suborder of Aquepts requires higher soil moisture conditions compared to the other suborders of Inceptisols.

Vegetation: Inceptisols occur under forested ecosystems, grassland or agricultural land. Although Inceptisols are not limited to forest environments, most of the soils classified into this order occur under forest ecosystems. Some Inceptisols (Umbrepts) were probably developed under prairie vegetation. Present use may be restricted by the shallowness of the solum (e.g. on steep slopes) or by poor drainage (e.g. in depression areas). Those Inceptisols are suited only to forestry and/or wildlife habitat.

Relief: Most Inceptisols develop on steep slopes where soil erosion removes parts of the topsoil continuously. Other Inceptisols are formed on convex toeslope areas where slope is level to gently rolling. These Inceptisols develop in deep colluvium where sediment has been / is deposited.

Parent Material: Inceptisols are extensive in areas of glacial deposits or on recent deposits in valleys or deltas. Where they occupy upland positions on young geomorphic surfaces, both primary and secondary minerals are present. Most Inceptisols are present on geologically young sediments (e.g. alluvium, colluvium, loess). Parent materials which is highly calcareous or resistant to weathering inhibit soil development but favor the development of Inceptisols.

Time: Most Inceptisols are formed on young landscapes (< Holocene), where time limited the development of soil diagnostic features. There are Inceptisols where the solum is permanently altered by loss of soil particles due to erosion or by the deposition of soil particles. These processes might be acting smooth but continuously or sporadically in space and time. In tropical zones the speed of development of Inceptisols into other soil orders is greater than in temperate or cold zones, it may be slowed down by retarded weathering of resistant rocks.

12.7.2) Processes

Virtually many pedogenic processes are active to some extent in Inceptisol profiles but none predominates. The genesis of Inceptisols includes multiple pathways depending on the processes occuring on a given landscape and geographic area. Environmental factors can slow down weathering (e.g. low temperatures, low precipitation, or resistant parent material) and soil development to form other soil orders is retarded or even inhibited.

Soil erosion on steep slopes can alter the topsoil extremely. When erosion has leveled the slope erosion rates become lower and more distinct pedogenic features like argillic horizons are formed. Usually Inceptisols are formed in underlying volumes of parent material as erosion lowers the landscape by removing the volume of material that was soil. Long time periods and high erosion rates are necessary to develop an Inceptisol on a steep slope (shallow soil, AC horizons) to a further developed soil (deep soil profile, ABC horizons).

Inceptisols form also in colluvium at the base of steep slopes. Processes to form colluvium are mass movement, soil creep (slow mass movement), and deposition. Due to the hillslope processes and weathering morphological features are being formed and destroyed continuously.

Inceptisols may be also found on alluvial deposits where temporary flooding alters the soil profile due to the deposition of soil particles on the soil surface and the soil profile becomes saturated. For example, Inceptisols in the southern Mississippi River Valey are developed on alluvial deposits. A high water table favors the reduction of iron and aluminium oxides.

In depression areas or valley bottoms poorly drained Inceptisols are found where gleization produces redoximorphic features. In those areas leaching may be more extensive than in other landscape positions, but the process of lessivage and thus argillic horizon formation is somewhat retarded, probably because the soils do not undergo frequent desiccation. In areas of acid rocks, soils formed in landscape depressions tend to be more leached and somewhat lower in base content than soils in surrounding areas. In landscapes of high base status soils, the associated poorly drained Inceptisols in depression areas usually have higher base status than the surrounding soils. This can be attributed to the enrichment of the low-lying parts of the landscape by lateral processes such as transport of bases attached to soil particles, in surface runoff, or lateral subsurface flow. In some materials saturated with brackish water sulfides may accumulate and sulfuric horizons may be formed. When oxidized, usually by artificial drainage, sulfuric acid is formed. These unique Inceptisols are commonly known as 'cat-clays'.

Decomposition, humification, and mineralization result in the accumulation of organic matter. The soil organic matter is higher in the suborders Umbrepts and Aquepts compared to the suborder Ochrepts.

12.7.3) Properties

The cambic subsurface diagnostic horizon of Inceptisols is composed of very fine sand, loamy fine sand or finer texture, with some weak indication of either an argillic or spodic horizon, but not enough to qualify as either. Typically, these soils have an ochric or umbric epipedon over a cambic horizon. The ochric epipedon is generally a light-colored, low organic matter horizon. The umbric epipedon is similar to the mollic epipedon except for having a base saturation less than 50 %. Some poorly drained Inceptisols have a histic epipedon where organic matter content is high. Soils with mollic epipedons are Inceptisols when base saturation at pH 7 is less than 50 % in some horizon between the mollic epipedon and a depth of 180 cm or a lithic or paralithic contact if shallower.

Shallow Inceptisols show only few horizons, for example AC, AR or ABC. Due to erosion the development of soil structure is weak.

12.7.4) Classification

The requirements to qualify for an Inceptisol are the following:

- Usually a cambic diagnostic horizon is present but no spodic, argillic, kandic, natric, or oxic horizon

- Soils that lack subsoil development but have umbric, histic, or plaggen epipedons

- Soil texture: loamy or finer textured mineral soils

- They exhibit profile development sufficient to exclude them from Entisols but lack features though to represent mature soil formation

- No andic soil properties are permitted in any layer thicker than 35 cm within the top 60 cm

- No aridic soil moisture regime is allowed

The suborders of Inceptisols are distinguished by soil moisture, epipedon properties, and soil temperature regime (Figure 18.1.4.1).

Figure 18.1.4.1. Diagram showing some relationships between suborders of the Inceptisols

- Aquepts: They show redoximorphic features and are saturated with water at some period in the year. Aquepts usually have cambic horizons and commonly in the US, they have fragipans. Aquepts are found in the Flood Plains of the Mississippi River Valley, the lacustrine regions in the Midwest, and the lower Coastal Plain along the Atlantic and Gulf Coast.

- Plaggepts: They have dark brown or black plaggen epipedons. Plaggepts were formed by anthropic activity mainly in Europe and are of small extent.

- Tropepts: They are formed in isomesic or a warmer iso soil temperature regime.

- Ochrepts: They have an ochric epipedon or if their soil temperature regime is mesic or warmer they have thin (< 25 cm) mollic or umbric epipedons. Their soil organic matter content is low.

- Umbrepts: They have umbric, mollic, or anthropic epipedons. They are freely drained Inceptisols that are acid, dark reddish or brownish, and high in organic matter.

Soil properties, soil temperature and moisture regimes distinguish the great groups and subgroups of Inceptisols.

Cryic or pergelic soil temperature (e.g. Cryaquepts), ustic moisture regime (e.g. Ustochrepts, Ustic Humitropepts), and aridic moisture regime (e.g. Aridic Ustochrepts) is considered in the Inceptisol Order.

A sulfuric horizon is considered on the great group (e.g. Sulfaquepts) and subgroup level (e.g. Sulfic Cryaquepts). The presence of a fragipan (e.g. Fragiaquepts, Fragic Epiaquepts, or Fragic Xerochrepts), a duripan (e.g. Durochrepts), or plinthite (e.g. Plinthaquepts) are considered. Carbonates within the soil profile of Inceptisols or a high base status define the Eutrochrepts. Inceptisols low in bases are common on the great group level (e.g. Dystropepts) and on the subgroup level (e.g. Dystric Eutrochrepts, Dystric Xerochrepts).

Shallow soil profiles are found in several subgroups, for instance, Lithic Ustochrepts, Lithic Cryaquepts, and Lithic Endoquepts. Vertic characteristics such as cracks and the extensibility of the mineral component of the soil define several subgroups of Inceptisols (e.g. Vertic Ustochrepts, Vertic Eutrochrepts, or Vertic Humitropepts).

Fluvial parent material is considered in several subgroups, for example, Fluventic Humitropepts, Fluventic Ustochrepts, or Fluventic Xerumbrepts. Inceptisols formed on volcanic material (e.g. volcanic glass) which does not meet the criteria of the Andisol order are considered by the formative element 'vitrandic' (e.g. Vitrandic Humitropepts, Vitrandic Durochrepts) or 'andic' if the fine-earth fraction exhibits a bulk density of 1.0 g/cm^3 or less (e.g. Andic Durochrepts, Andic Fragiochrepts).

12.7.5) Distinguishing Characteristics

Inceptisols include soils that have some subsoil development but lack features of other soil orders. They are excluded from the Aridisol order by soil moisture regime, from the Vertisol order by lack of argillipedoturbative features, and from the Andisol order by andic parent material. In temperate climate and increased precipitation Mollisols or Alfisols are formed. In tropical and subtropical climate Ultisols or Oxisols are formed.

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12.8) Mollisols

Summary:

- Vegetation: prairie, grassland

- Climate: variety of soil temperature regimes (cryic to hypothermic)

- Soil moisture regime: variety of soil moisture regimes - aquic, udic, ustic, or xeric; average annual precipitation between 200 to

800 mm

- Major soil property: organic matter content, high base saturation,

- Diagnostic horizons: argillic, cambic (natric, calcic, petrocalcic, gypsic, albic, duripan)

- Epipedon: mollic

- Major processes: melanization, decomposition, humification, pedoturbation

- Characteristics: highly fertile soils

12.8.1) Environmental Conditions

➢ Climate: Mollisols occur in a variety of climatic zones, ranging from cryic (e.g. Mongolia, North Dakota), frigid (e.g. Iowa), mesic (e.g. Pakistan), or thermic (e.g. central Oklahoma) temperature regimes. The average annual precipitation amount ranges from 200 mm where short-grass steppe vegetation predominates to 800 mm where tall-grass vegetation grows. For example, climate in the Great Plains favor the development of Mollisols: severe, dry winters with much wind and relatively slight accumulation of snow; relatively moist springs and droughty summers with some thunderstorms and/or tornadoes (e.g. typical climate of the Great Plains). Mollisols occur under several soil moisture regimes: udic, ustic, xerix, and aquic.

➢ Vegetation: Most of the Mollisols have formed under prairie or grassland vegetation. There are different types of prairie: In tall-grass prairie grasses stand 1 to 3-m at maturity, whereas in short-grass prairie grasses stand 13 to 30-cm in height. The prairie or grassland vegetation add plentiful raw organic matter to the soil, mostly by in situ root death. Legumes in the prairie or grassland community contribute considerable nitrogen to the soil. Prairies develop under relatively moist condistions, whereas grass steppe develop under drier climate. Prairie extension was largest approximately 5000 to 2000 B.P. Common species of prairie vegetation are bluestem (Andropogon gerardi), buffalo grass (Buchloe dactyloides), or western wheat grass (Agropyron smithii). Nowadays, most of the prairie in the U.S. is replaced by farmland. Mollisols are fertile soils and in the U.S. approximately 25 % of the land area are covered by Mollisols which produce much of the wheat, soybean, and alfalfa yield. A few Mollisols have formed under forest, under special conditions of poor drainage and/or calcareous or high base status parent material.

➢ Relief: Mollisols cover a wide range of land forms (e.g. flat or gently rolling plains, undulating plains, mountain areas). Extensions of prairies by fire have formed preferentially on topography over which fire moves easily (e.g. ridgetops, windward slopes).

➢ Parent Material: Mollisols occur on deposits and landscapes with a wide range of ages. Many Mollisols are formed on deposits associated with glaciation (unconsolidated Quaternary materials), where calcareous rich aolian deposits supported the formation of Mollisols. However, in other areas they develop in residuum weathered from sedimentary rocks.

➢ Time: The age for development of Mollisols is indifferent and closely associates to the other environmental factors.

12.8.2) Processes

Melanization is defined as a process of darkening of the soil by addition of organic matter and it is the dominant process in Mollisols. Thus, the melanization that occurs in Mollisols is driven by the incorporation of organic matter directly into the mineral soil.

The prairie and grassland vegetation accumulate relatively large amounts of organic matter (accumulation of OM). Microbial decomposition of organic materials in the soil produces relatively stable, dark compounds (humification). Residue from plants partially decomposes on the soil surface and enriches the upper part of the A horizon through incorporation by soil fauna. Earthworms, ants, cicada nymphs, and rodents (e.g. gophers) are considered to be important agents in promoting the incorporation and breakdown of litter into the soil. The biological activity in Mollisols is greater than in forest soils, particularly the earthworm activity is considerable in Mollisols. Intensive pedoturbation obliterates the differentiation of horizons. In Mollisols several kinds of pedoturbation are recognized: (i) Faunal pedoturbation: soil mixing by animals such as ants, earthworms, moles, and rodents, (ii) Human induced pedoturbation: tillage operations, (iii) Congelli pedoturbation (cryoturbation): mixing by freeze-thaw cycles as in tundra and alpine landscapes, and (iv) Argilli pedoturbation: mixing of materials in the solum by shrink and swell movements of expansible clays as they wet and dry in the water cycles within the soil.

In some Mollisols there is also evidence of eluviation and illuviation of organic and some mineral colloids (clays, iron and manganese oxides) along voids between peds and the surfaces of which become coated with dark cutans (organo-argillans). For example, an eluviated horizon is present in the Albolls and an argillic horizon is found in Argiudolls. Percolation of water is influenced by systems of cracks, krotovinas, and macropores made by roots and soil fauna. In many medium-textured, well-drained Mollisols the presence of A and B horizons with nearly equal clay content can be explained by the following processes: (i) in climates where evapotranspiration exceeds precipitation clay might be translocated upwards from the B to the A horizon, (ii) rapid clay formation in the A horizon under well-drained soil moisture conditions and grassland vegetation, (iii) very slow eluviation in grassland soils, due to the complexing of mineral and organic colloids and the rapid adsorption of water by plant roots, or (iv) pedoturbation by prairie ants (Formica cinerea), which builds mounds where clay, organic material, phosphorus, and potassium is accumulated.

Deposition of loess material (dust) and blown out dry organic matter support the development of Mollisols (wind erosion). The deposited material is rich in calcium and other nutrients, which supports microbial activity. In many Mollisols the calcareous loess was leached of carbonates and varying degrees of acidity have developed. After leaching of carbonates, clay formation reaches its maximum and clay movement might occur when precipitation exceeds evapotransiration.

Water erosion can cause cumulization and the thickening of the mollic epipedon. These soils usually are at the base of slopes or on flood plains. They are defined by the denotion 'cumulic'. In intensively cultivated areas, as in the Midwest, many of the soils have lost a significant thickness of the surface horizon due to erosion.

12.9.3) Properties

12.9.3) Properties

A major characteristic of Mollisols is the high accumulation and decomposition of soil organic matter (SOM). SOM includes a variety of materials ranging form newly added material to the thoroughly decomposed and polymerized residual matter (humus). The grassland or prairie vegetation produce high amount of SOM, where as much as 80 % of the total biomass is in the roots. For example, the above-ground production of tall-grass prairie ranges from 1700 to 3500 kg/ha, whereas the dry weight of roots is about 3 times higher. Under prairie vegetation more than 50 % of the biomass is added to the soil annually, almost all the above ground parts and at least 30 % of the underground parts. As a result, most of the OM is deposited within the profile itself, the highest amount within the mollic epipedon. Due to decomposition and humification stable humus is formed, which is composed of complex organic compounds synthesized by the soil organisms and resistant polymers of phenolic and aromatic functional groups. The average C:N ratio for grassland soils is nearly constant, ranging from 10:12. Mollisols exhibit a mollic epipedon, which is dark in color, humus-rich, relatively fertile, and show a thickness of about 40 to 75 cm. If earthworm activity is high wormholes or macropores are formed which are pathways for preferential flow. Additional factors that are associated with the accumulation of organic matter in Mollisols are a high base saturation (> 50 %), high cation exchange capacity, and a high water holding capacity.

Generally, the A horizon shows a granular structure, whereas the B horizon exhibits blocky and prismatic soil structure. Many clay minerals have been formed from pedogenesis. Inherited micas have been depleted of potassium and valence charges of the layers have been lowered by weathering producing a wide array of clay minerals in Mollisols. Coatings are found on ped surfaces, which are called organo-argillans composed of mineral and organic components. The eluviation and illuviation of clay might form an argillic or a cambic diagnostic horizon. Because the formation of the argillic horizon is relatively slow, its presence in Mollisols indicates soils formed on older, more stable geographic surfaces. Krotovinas (filled burrows) develop due to the intense activity of the fauna.

12.10.4) Classification

While it is true that all Mollisols have mollic epipedons, the presence of a mollic epipedon does not automatically qualify a soil as a Mollisol. Epipedons that are made to meet the mollic criteria by the common practice of agricultural liming are excluded from criteria when placing a soil in the Mollisol order.

The criteria to qualify for a Mollisol are:

- Mollic epipedon
- Base saturation of 50 % or more in all horizons to a depth of 180 cm or a lithic or paralithic contact if shallower

There are 7 suborders in the Mollisol order:

- Albolls: Albolls are Mollisols with an albic horizon, aquic conditions for some time in most years, and redox concentrations within 100 cm of the mineral soil surface. Below the albic horizon there is an argillic or natric horizon. Processes which develop Albolls are eluviation/illuviation and reduction of iron and manganese oxides due to wet soil moisture conditions. They occur on nearly level interfluve ridgetops or closed depressions.

Aquolls: They develop under aquic conditions thus they show soil properties associated with wetness: (i) redoximorphic features, (ii) accumulation of organic matter, (iii) a histic epipedon overlying the mollic epipedon, (iv) accumulation of calcium carbonate or exchangeable sodium near the soil surface.

Rendolls: They are formed in humid regions under forest, formed from calcareous parent materials (e.g. limestone, calcareous glacial till, chalk, shell deposits). The mollic epipedon must be less than 50-cm thick and may be rather weakly expressed due to the dilution effect of the light-colored, calcium-rich material from which it has formed. Rendolls do not have argillic or calcic horizons. This suborder is not subdivided into great groups, but a number of subgroups are identified on the basis of a shallow lithic contact, cryic soil temperature regime, vertic character, and presence or absence of a cambic horizon. They were classified as Rendzina in the previous U.S. classification.

Xerolls: Xerolls are Mollisols that have a xeric soil moisture regime. They ordinarily have a thick mollic epipedon, or cambic or argillic horizon and an accumulation of carbonates in the lower solum. They occur in the U.S. in Washington, Idaho, and Oregon.

Cryolls: This is the most extensive Mollisol suborder worldwide. Borolls form under a frigid and cryic soil temperature regime. They occur in Eastern Europe and Asia (the northern Russian steppes), and the northern Great Plains and in mountainous areas of the western United States.

Ustolls: That are the freely drained Mollisols of semiarid to subhumid climates with ustic soil moisture regime. Erratic rainfall occurs mostly during the growing season, and summer drought is a frequent, but erratic occurence. They are the most extensive Mollisols in the U.S. found in the southern Great Plains, New Mexico, Texas, and Oklahoma. Most Ustolls show an accumulation of calcium carbonate in the soil profile (calcic horizon).

Udolls: Udolls are formed under udic soil moisture regime in continental climates of the temperate and tropical regions. They were formed on late-Pleistocene or Holocene glacial or other deposits, under tall-grass prairie. Their well-developed mollic epipedons usually are underlain by either argillic or cambic horizons. They occur in the western Corn Belt of the U.S. and in the humid parts of the South American Pampas.

Several soil moisture regimes are considered at subgroup level ranging from dry to wet conditions: Xeric (e.g. Xeric Argialbolls), aridic (e.g. Aridic Calcixerolls), udic (e.g. Udic Paleustolls), ustic (e.g. Ustic Argicryolls), and aquic (e.g. Aquic Natrustolls).

Great groups and subgroups are differentiated by subsurface diagnostic horizons: (i) argillic - e.g. Argialbolls, Argic Duraquolls, (ii) natric - e.g. Natraquolls, Natric Duraquolls, (iii) calcic - e.g. Calciaquolls, Calcic Haplocryolls, (iv) petrocalcic - e.g. Petrocalcic Palexerolls, (v) gypsic - e.g. Clcixerolls, (vi) albic - e.g. Albic Cryoborolls,or (vii) duripan - e.g. Duricryolls, Duric Natrixerolls (viii) cambic - e.g. Eutropeptic Rendolls.

Soils formed in volcanic parent material with low bulk densities (< 1.0 g/cm^3) and more than 35 % fragments coarser 2.0 mm are denoted by 'andic', 'aquandic', or 'vitrandic' (e.g. Andic Cryoborolls, Aquandic Argialbolls, Vitrandic Durixerolls).

The term 'vertic' is used when Mollisols show characteristics such as cracking, wedge-shaped aggregates, slickensides, and high content of expandable clays (e.g. Vertic Cryaquolls, Vertic Haprendolls, Vertic Palexerolls).

Mollisols with a glossic horizon, i.e., interfingering of albic material into the subsurface horizon is called 'glossic' (e.g.Glossic Natriborolls, Glossic Natrustolls).

Some Mollisols are differentiated by soil texture. Mollisols that have a sandy or sandy-skeletal particle-size class throughout a layer extending from the mineral soil surface to the top of an argillic horizon at a depth of 50 cm to 100 cm are denoted as 'arenic' (e.g. Arenic Argiaquolls , Arenic Argiborolls). Other Mollisols that have a mollic epipedon 50 cm or more thick with a texture finer than loamy fine sand are called 'pachic' (e.g. Pachic Haplustolls, Pachic Argiustolls). Mollisols that have a sandy particle-size class throughout the upper 75 cm of the argillic horizon, or throughout the entire argillic horizon if it is less than 75 cm thick are classified as 'psammentic' (e.g. Psammentic Argiudolls).

The thickness of the mollic epipedon differentiates Mollisols using the denotion 'entic'. For example, the mollic epipedon has to be less than 50 cm thick in Entic Vermustolls and less than 75 cm thick in Entic Vermudolls. Shallow Mollisols are classified as 'lithic' (e.g. Lithic Endoaquolls, Lithic Rendolls, Lithic Argicryolls). Thicker mollic epipedons are classified as 'cumulic', where the epipedon has to be > 50 cm thick (e.g. Cumulic Cryaquolls).

Mollisols with a high amount of wormholes, worm casts, or filled animal burrows are classified as 'vermic' (e.g. Vermudolls).

There are Mollisols with a histic epipedon (e.g. Histic Cryaquolls) and soils with a mollic epipedon which are actual buried Histosols that has its upper boundary within 100 cm of the mineral soil surface (e.g. Thapto-Histic Cryaquolls).

Wet soil moisture conditions form aquic or even oxyaquic Mollisols, where redoximorphic features are present (e.g. Aquic Natrixerolls, Oxyaquic Argiborolls).

Mollisols where the argillic horizon has its upper boundary 60 cm or more below the mineral soil surface are classified by the term 'pale' (e.g. Paleborolls). In those soils the argillic horizon is the result of an earlier weathering regime no longer present.

12.10.5) Distinguishing Characteristics

In Mollisols the significant characteristic is the presence of a mollic epipedon. There are similar soils which show a dark, humus-rich surface horizon high in exchangeable calcium and magnesium. Differences in chemical composition (e.g. phosphorus content) differentiate Mollisols from other soils with similar morphology but different genetic histories. The mollic epipedon may occur in soils of other orders in addition to Mollisols. Mollic epipedons are present in many Vertisols, in which case the plastic, shrink-swell nature of the clay is a more significant soil property than the mollic epipedon. Also, mollic epipedons are found in the

Inceptisol order with cambic horizons that more significantly influence the profile than does the mollic epipedon, which in some cases may have been formed by lime applications. A few Alfisols also have mollic epipedons where nutrient cycling has extensively removed bases from the subsoil and concentrated them in the epipedon.

Prairie soils such as Argiudolls will develop into Albaquolls as weathering, clay production, and horizon differentiation proceed. Failure to meet the thickness criteria for a mollic epipedon results in potential classification of many of these soils as Mollic Hapludalfs if they are well drained and have an argillic horizon. Without an argillic horizon but with a cambic horizon in the profile, they are classified as Inceptisols.

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12.11) Oxisols

Summary:

- Vegetation: wide range of vegetation types
- Climate: isomesic to isohyperthermic, favourable in isotropical zones
- Soil moisture regime: aridic to perudic
- Major soil property: high content of 1:1 type clays, presence of highly insoluble minerals such as quartz sand and sesquioxides, low CEC
- Diagnostic horizons: oxic, kandic
- Epipedon: ochric
- Major processes: weathering, desilication, pedoturbation
- Characteristics: most Oxisols occur on geologically old and highly weathered parent material; virtually absence of weatherable primary minerals or 2:1 type clays

12.11.1) Environmental Conditions

Climate: Oxisols occur within the range from isomesic to isohyperthermic regimes but most Oxisols develop in isotropical soil temperature regimes. Broadly speaking, they develop in climatic zones with small seasonal variation in soil temperature and no seasonal soil freezing. They occur under a wide range of soil moisture regimes from aridic to perudic. Oxisols occuring under aridic moisture regimes are often considered as relicts. It is assumed that Oxisols develop under climatic conditions where precipitation exceeds evapotranspiration for some periods of the year to favor the removal of soluble weathering products and favors the formation and residual concentration of kaolinite and sesquioxides, which are essential to form an oxic diagnostic horizon.

Vegetation: Oxisols may occur under a wide range of vegetational zones including tropical rainforest, scrub and thorn forest, deciduous forest, and savannah (e.g. in the central Brazilian plateau). The use of Oxisols is often limited to shifting cultivation, subsidence farming, low-intensity grazing. Due to amendments Oxisols can be used also for the growth of soybeans, wheat, corn, and coffee (intense plantation agriculture).

Relief: Most Oxisols occur either on relatively stable upland summit positions, relict from a previous regional erosion surface, or on preserved remnants of an old alluvial terrace, which are nearly level topography. Oxisols are not likely to occur on steep slopes.

Parent Material: Oxisols occur on highly weathered transported material, old fluvial terraces, or on high-lying old erosion surfaces. The most extensive areas of Oxisols are in sediments that have been reworked during several erosional and depositional cycles, some extending to the earliest geologic eras, although they may also form in materials which wheather rapidly.

It has been suggested that Oxisols result because of the geologic history of the parent material prior to pedogenic conditions at the present site. It can be reasoned that if the parent material consists of only quartz, 1:1 type clays, and iron and aluminum oxides and hydroxides, few pedogenic processes are possible, and a soil formed in such material will have Oxisol properties regardless of present or past climate at the site.

Time: Most of the Oxisols are formed on transported materials (erosion) where desilication (loss of silica) and intense weathering has taken place over vast expanses of times (about 50,000 y up to 100,000 y or even longer).

12.11.2) Processes

Oxisols may be classified into two categories: (i) formed in situ rocks or sediments, and (ii) formed on preweathered and transported sediments.

Weathering is very intense in Oxisols showing a weathering depth much greater than for most of the other soil orders - 16 m or more having been observed. Because of weathering most of the primary minerals and 2:1 type clay minerals are transformed to 1:1 type minerals such as kaolinite and gibbsite and secondary iron and aluminum oxides and hydroxides. The formation of free non-silicated alumina (e.g. gibbsite) requires the rapid and almost immediate removal of soluble weathering products (basic cations), particularly silica (desilication). These processes are supported by free drainage conditions, intense rainfall, and a position well above the water table, where ferrous ions (Fe^{2+}) produced by hydrolysis are oxidized immediately and are thus eliminated from the reaction by precipitation into ferric forms (Fe^{3+}). In tropical zones hydolysis and oxidation are increased compared to temperate zones, and heavy rainfall continuously removes dissolved reaction products. When removal of silica does not reach its extreme to form gibbsite kaolinite is formed, which is typical for intertropical climate. Lower original silica contents, higher rainfall and temperatures will generally increase the gibbsite content.

The parent material determines the intensity of weathering. Acid igneous rocks (e.g. granite) weather at a slower rate as basic rocks (e.g. basalt). Granitic saprolites are often several meters thick and primary minerals may for a long time continue to weather and the slow hydrolysis of feldspars, biotites, and amphiboles supply silica to the soil solution as to favor the formation of kaolinite. Slower transformations, as in granitic saprolites, will essentially produce kaolinite. The iron content of the oxic horizon formed under free drainage and good aeration will be a function of the original compostion of the parent material.

Clay translocation is not a major pedogenetic process taking place in oxic horizons because the clays in oxic materials have a low potential mobility, i.e., dispersion of clays and subsequent migration does not occur extensively. At the oxic stage neoformation of clay is practically nil, and consequently freshly formed clays, which tend to move more readily, are absent.

Humification takes place in all Oxisols. In regions with warm or high temperatures year-around litter humifies and mineralizes rapidly. The organic matter content in Oxisols is indirectly proportional to soil temperature. In general, Oxisols are not as dark in color at similar organic matter contents as soils of the other soil orders. Organic acids provided by decomposition and humification destabilize the soil micro-aggregates and produce water dispersable clays, which are subsequently leached. In general, organic acids tend to retain silica, iron and aluminum are complexed and leached out. When water is the sole leaching agent, the process, in terms of the products formed, leads to the residual concentration of sesquioxides, which is a component of the formation of oxic horizons.

Faunal pedoturbation is a major process in most Oxisols. This process of intense disturbance and mixing of soil is due to activity by insects, particularly termites. Due to pedoturbation numerous mounds may be formed at the soil surface. Pedoturbation by treethrow does also prevent or retard soil horizonation.

12.11.3) Properties

Oxisols show an oxic or kandic subsurface diagnostic horizon. An oxic horizon has to be at least 30-cm thick and is sandy loam or finer. It has a high content of low-charge 1:1 clays with an effective cation exchange capacity (ECEC) of <= 12 cmol kg^{-1}clay and a cation exchange capacity (CEC) of <= 16 cmol kg^{-1} clay at pH 7. Weathering and intense leaching have removed a large part of the silica from silicate minerals in this horizon (low nutrient reserve). Although the clay content in Oxisols is often high the CEC is low. This is due to the almost complete weathering of primary minerals and 2:1 type clay minerals to 1:1 type minerals such as kaolinite and gibbsite. Those minerals are not expandable secondary minerals and their CEC is low. The permanent charge of kaolinite and gibbsite is low but they may develop a small but significant pH dependent charge due to their low crystallinity. The most common structure of oxic horizons in soils on old geomorphic surfaces is massive separating into very fine crumbs. The primary aggregates built up of individual particles are held together by clay-sized substances. Bulk desities of the oxic horizon are usually in the range from 1 to 1.3 g cm^{-3}. The oxic horizon contains less than 10 % weatherable minerals and has < 5 % by volume rock structure.

The oxic horizon is generally very high in clay-size particles dominated by hydrous oxides of iron and aluminum. Most of the sesquioxides are generally goethite or hematite although maghemite may also be present in soils derived from basic rocks. Most clay-size minerals found in the oxic horizon are poorly crystallized. Generally, poorly crystallized Al and Fe-oxides may form more effective bonds between particles compared to better crystallized Al and Fe-oxides, which are poor cementing agents. This indicate that the composition of sesquioxides is as important as their quantity for structural stability of a soil.

Oxisols are classified by the presence of an oxic or a kandic horizon. Kandic horizons show the same ECEC and CEC as oxic horizons but kandic horizons have a clay content increase at its upper boundary of > 1.2 x clay within a vertical distance of < 15 cm, i.e., abrupt or clear textural boundary.

A fluctuating water table (alternating oxidation - reduction) in Oxisols may form plinthite consisting of red-and-gray mottled material. In the past this material has been designated as 'laterite' or 'lateritic iron oxide crust'. If subjected to repeated wetting and drying, as in exposure by erosion of overlying material, it becomes indurated to ironstone, which may be subsequently erode and be deposited as ironstone gravel layers in alluvial fans.

Infiltration and percolation rates in Oxisols are rapid. Many Oxisols bahave like sandy textured soils with respect to their pF curves, i.e., the water holding capacity is limited.

12.11.4) Classification

To qualify for an Oxisol the requirements are:

- Oxic diagnostic horizon within 1.5 m of the mineral surface of the soil, or
- if the surface 18 cm exceeds 40 % clay content, a kandic diagnostic horizon.
- The oxic or kandic horizon must contain less than 10 % weatherable minerals in the sand fraction

Almost all Oxisols occur in South America and Africa. No Oxisols have been reported in the continental United States. There are 5 suborders, whereas classification is based on the soil moisture regime:

- Aquox: Oxisols that have aquic conditions for some time in most years and show redoximorphic features or a histic epipedon are defined as Aquox.
- Torrox: The suborder of Torrox classifies Oxisols with an aridic soil moisture regime.
- Ustox: The suborder of Ustox classifies Oxisols with an ustic or xeric soil moisture regime.
- Perox: The suborder of Perox classifies Oxisols with a perudic soil moisture regime.

Udox: The suborder of Udox classifies Oxisols with an udic soil moisture regime.

Oxisols are classified by 'Acr' (e.g. Acraquox, Acrustox) when the soil profile is highly weathered and the ECEC is less than 1.50 cmol(+)/kg clay and the pH value is 5.0 or more, that are soils with negligible amounts of exchangeable cations (including aluminum).

The 'Eutr' great group of Oxisols are high base status soils, i.e., base saturation of 35 percent or more in all horizons within 125 cm of the mineral soil surface. Their high base status is attributed to enrichment during brief periods of saturation by lateral subsurface flow and lateral transport of nutrients (e.g. Eutraquox, Eutrotorrox, Eutric Acrustox).

Oxisols that have plinthite forming a continuous phase within 125 cm of the mineral soil surface are designed as 'Plinthic' (e.g. Plinthaquox, Plinthic Acroperox).

Diagnostic horizons such as 'Sombric' (e.g. Sombriustox), 'Kandic' (e.g. Kandiustox), and epipedons such as 'Histic' (e.g. Histic Eutraquox) are used to classify Oxisols at the great group and subgroup level.

Oxisols that have a lithic contact within 125 cm of the mineral soil surface are classified as 'Lithic' (e.g. Lithic Sombriustox, Lithic Acrotorrox, Lithic Acroperox). Oxisols that have a petroferric contact within 125 cm of the mineral soil surface are classified as 'Petroferric' (e.g. Petroferric Sombriustox, Petroferric Acroperox). Petroferric contact is a boundary between soil and a continuous layer of indurated soil in which iron is an important cement.

Oxisols, where the oxic horizon has its lower boundary within 125 cm of the mineral soil surface are called 'Inceptic' (e.g. Inceptic Eutrustox, Inceptic Eutroperox).

Oxisols with a high organic matter content are classified as 'Humic' (e.g. Humic Sombriustox, Humic Acroperox, Humic Kandiperox), which must have 16 kg/m^2 or more organic carbon between the mineral soil surface and a depth of 100 cm.

Oxisols that have a delta pH (KCl pH minus 1:1 water pH) with a 0 or net positive charge in a layer 18 cm or more thick within a depth of 125 cm of the soil surface are classified as 'Anionic' (e.g. Anionic Acrustox).

Soil moisture regime defines 'Aquic' Oxisols at subgroup level (e.g. Aquic Acrustox, Aquic Kandiperox), which show redox depletions with a color value, moist, of 4 or more and a chroma of 2 or less. Oxisols which show redox depletions with a color value, moist, of 4 or more and a chroma of 2 or less, and also aquic conditions for some time in most years are called 'Aqueptic' (e.g. Aqueptic Haplustox). Oxisols that are saturated with water, in one or more layers within 100 cm of the mineral soil surface, for 1 month or more per year in 6 or more out of 10 years are classified as 'Oxyaquic' (e.g. Oxyaquic Haplustox).

Soil color is used at subgroup level: 'Rhodic' (a hue of 2.5YR or redder; and a value moist of 3 or less) - e.g. Rhodic Acrustox; 'Aeric' , which have, directly below an epipedon, a horizon 10 cm or more thick that has 50 percent or more chroma of 3 or more (e.g. Aeric Acraquox); 'Xanthic' (a hue of 7.5YR or yellower and color value, moist, of 6 or more between 25 and 125 cm from the mineral soil surface (e.g. Xanthic Acrustox).

12.11.5) Distinguishing Characteristics

Many soils have an argillic or kandic horizon but do not qualify as Oxisols because they do have less than 40 % clay in the surface 18 cm and classify as Ultisols or Alfisols.

Soils with more than 10 % weatherable minerals in the sand fraction classify as Inceptisols. For example, Quartzipsamments occupy areas, where superficial materials are sandy. They are closely associated to Oxisols.

Oxisols may include many soils previously called Laterites or Latosols, which are formed in tropical or subtropical regions.

Oxisols formed on high-lying old erosion surfaces (plateaus), terraces or floodplains are associated with Ultisols, Alfisols, or Mollisols on the sideslopes. Entisols may occur on floodplains or steep rapidly eroding areas.

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12.12) Spodosols

Summary:

- Vegetation: coniferous or mixed coniferous/deciduous forest, heath vegetation, ericaceous shrubs, alpine grasses, sedges
- Climate: Major settings in the humid boreal climatic zone
- Soil moisture regime: mostly udic (xeric, aquic)
- Major soil property: placic horizon, ortstein, coarse soil texture, low exchangeable bases, low pH
- Diagnostic horizons: spodic, (albic)
- Epipedon: histic, plaggen, umbric, or ochric
- Major processes: podzolization
- Characteristics: Soils with subsoil accumulation of humus and sesquioxides

12.12.1) Environmental Conditions

Climate: Spodosols may have any soil temperature regime. They are largely confined to humid areas that extend from high latitudes to the tropics. But, especially extensive in cool-humid, mid to high latitudes, e.g. Alaska, Northern Gt. Lakes, Canada, Northern New England, and comparable bioclimatic zones in Europe, Soviet Union, Japan, Argentina and New Zealand. Intertropical areas include coastal plains of Florida, Madagascar, Brazil, Australia, Brazil and Surinam. When they form in hot, humid tropical regions and other warm, humid areas, they occur mostly in quartz-rich sands that have fluctuating level of ground water. The moisture regime of Spodosols is mostly udic, but a few have a xeric moisture regime. Some have aquic conditions (suborder: Aquods).

Vegetation: The formation/occurrence of Spodosols is correlated with certain vegetation associations. Vegetation that can supply mobile and sesquioxide-mobilizing organic compounds favors the formation of Spodosols: (i) production of humic and fulvic acids (low molecular weight organics), (ii) vegetation with high cellulose contents / acidic, low-base litter, which decomposes slowly, and (iii) the release of phenolic and carboxylic compounds in throughfall and stemflow that are able to chelate or immobilize Fe an Al. Typical vegetation for Spodosol development are found in New Zealand - Kauri pine (Agathis australis); N-Hemisphere - Hemlock (Tsuga canadensis), Heath vegetation (Calluna vulgaris & Erica sp.), alpine grasses, sedges, and conifers (Pinus, Cupressus sp.); Spodosols are also found under Picea, Larix, Thuya, Populus, Quercus, Betula and understory plants such as Vaccinium.

Spodosols are used for forestry, pasture, hay, and for cultivated crops (e.g. blueberries). Management can decrease acidity by adding lime and raise nutrient level by fertilization. Ploughing mixes the O, A, or E horizon with the underlying horizon or break open cemented layers and degrades the spodic horizon to some extent due to aeration. In some European countries human activities such as burning, cutting, and grazing of heather by sheep preserve Spodosols. The rationale for these activities is to conserve those typical landscape settings with heather vegetation and Spodosols for future generations.

Treethrow is a common phenomenon in Spodosol dominated landscapes because of the shallow root system and rigid trunks, which is due to limited root penetration in cemented layers.

Relief: Spodosols form on slopes ranging from nearly level to very steeply sloping and on surfaces in which the water table ranges from very deep to fluctuating near the surface. They do not seem to form in a soil that is permanently saturated with water. The iron content of spodic horizons depends on the watertable levels - spodic horizons that are saturated with water for prolonged periods may be depleted of iron because it is reduced and mobilized.

Parent Material: Typically, Spodosols are formed in very coarse silty or coarser (i.e. increase in sand) textured material, e.g. sandy loam, loamy sand, sand. Siliceous or leached carbonaceous parent materials favor the development of Spodosols. In the United States most Spodosols occur in late-Pleistocene or Holocene deposits. Some materials were originally calcareous, but carbonates were leached before the spodic horizon developed. Spodosols form also in weathered material from rocks poor in Ca and Mg (e.g. sandstone, granite). The content of iron-bearing minerals in the parent material influences the kind of spodic horizon that will develop and the degree of development of an E horizon.

Time: In glaciated terrain Spodosols are relatively young - about 10,000 years. Some Spodosols are even younger when parent material, vegetation, and climate favors the formation of a spodic diagnostic horizon (<500 y). A cemented spodic horizon takes longer time periods to form (approximately 3,000 to 8,000 y).

12.12.2) Processes

Spodosols represent a more limited grouping of soils than that encompassed by Podzols (a grouping used in previous US classification systems and current systems in Europe, the Soviet Union and elsewhere). Podzol is a term from the Russian pod (beneath) and zol (ash), referring to the light-colored E horizon. In contrast to Podzols, Spodosols are not characterized by evidence of clay translocation, even though some may contain argillic horizons. Podzols differ from Spodosols in terms of the requirement of an eluvial and an illuvial horizon, whereas the requirement for Spodosols is only an illuvial spodic horizon.

Podzolization describes collectively the subprocesses of mobilization, eluviation of organic material, Al and Fe from the O, A, and E horizons, and the illuviation of these materials in the spodic horizon. The processes of Spodosol formation are complex and several hypotheses exist in literature.

Decomposition of surface litter, roots, and organisms produces organic acids (humic and fulvic acids). Leaching of any carbonates present, i.e., acidic condition in the upper horizons (O, A, and E horizons) is another prerequisite to the mobilization of organic matter and sesquioxides.

In general, a prerequisite for development of a spodic horizons is leaching of carbonates. In soils of high-base status microbial activity is generally vivid and organic materials tend to be oxidized or to form relatively insoluble Ca-humates. As depletion of bases occurs through leaching of soils in humid regions, bacterial decomposition of organic matter is retarded and minerals weather more rapidly releasing Al, Fe, and other elements. Soluble organic substances produced by fungi and other micro-floral and -faunal attack on plant litter persist and migrate downward with the soil solution. The development of Spodosols is forced under acidic, low-base litter by coniferous or mixed coniferous/deciduous forest, ericaceous shrubs, heath vegetation, alpine grasses, or sedges. Since the decomposing plant litter contains some Al and Fe taken up by plants, some soluble low-ratio (Al,Fe)-organic complexes may be formed directly in the O horizon that occur at the surface of most Spodosols.

Weathering of Spodosols is more intense towards the soil surface. Silt-sized silicates may weather to form mixed layer minerals (chlorite-vermiculite or chlorithe-mica) in the upper horizons. In the A and B horizons clay-sized quartz and feldspars is enriched. Inherited clay-sized silicates in the C horizon of Spodosols commonly include some combination of mica, chlorite and kaolinite. The marked difference in the extent of clay mineral weathering in the E and B horizon is though to be due to the fact that mineral surfaces in the B horizon are presumably coated with sesquioxides-organic surfaces and thus protected from weathering. Generally, ferromagnesian minerals near the surface are dissoluted and Fe, Al, Mg, Si, and associated elements are liberated.

There are several hypotheses describing the eluviation of material from the O, A, and E horizons to the illuvial (spodic) horizon:

I. Complexation of Fe and Al with organic acids: Humic substances can attack minerals and Al, Fe and other cations are liberated. Fe and Al build complexes with low molecular weight organics in surface horizons. The complexes are subsequently translocated in percolating water and precipitated in the B horizon. Continuing removal of weathering products from mineral surfaces by complexing action of organic solutions contributes to relatively rapid weathering in the E horizon, which is rich in quartz and other resistant minerals.

Soluble organic matter derived from decomposing plant litter has the capacity to remove Al and Fe from sesquioxide-organic complexes deposited in spodic horizons. If uncomplexed humic substances are added at a rate much faster than that of mineral weathering and release of Al and Fe in the solum, the sesquioxide-organic complex presumably attains a progressively lower metal to organic ratio and becomes increasingly soluble. Ultimately, the spodic horizon could be moved to a greater depth or destroyed and the low ratio complexes could move out with the percolating water.

Precipitation is assumed to occur because of changes in one or more of the following conditions in the subsoil: hydrology, chemistry and microbiology.

Precipitation of the (Al,Fe)-organic complexes might be related to the following mechanism (polymerization): Soluble humic substances form complexes with Al and Fe released from weathering surfaces of minerals in soil. Complexes having a low ratio of metal ion to carbon are soluble, but as loading increases, the complex becomes increasingly insoluble. The (Al, Fe)-organic complexes found in spodic horizons are commonly insoluble. Regardless of the process slow release of Al and Fe appears to be important, so that the metal-complex ratiois sufficiently small to maintain the complex soluble in the upper portion of the soil.

Alternatively, the low-ratio complex may be adsorbed by insoluble high-ratio(Al,Fe)-organic complexes already deposited or by Al and Fe hydroxides (chemisorption). The insoluble complex has the capacity to complex additional Al and Fe. Whatever the mechanism, the result is the same, the complex is deposited in soils with available sesquioxides. The site of deposition of sesquioxide-organic complexes depend upon the supply of weatherable minerals and disturbances such as faunal activity, blowdown of trees, etc.

Another mechanism for the precipitation of material in the spodic horizon is due to microbial oxidation of organic matter, hence Al and Fe translocated to the B horizon as organic complexes are deposited as hydrous oxides due to microbial oxidation. The weakness in this hypothesis is generally the decrease of microbial activity with depth in soil. Furthermore, the resistance to microbial breakdown of humic substances in spodic horizons is high.

It has also been suggested the idea of mutual flocculation of negatively (humic) and positively (sesquioxides) charged sols.

II. Reduction of Fe^{3+} - translocation of Fe^{2+} - precipitation as $Fe(OH)_2$: The removal of Fe from the O, A, and E horizons is due to reduction of Fe^{3+} to Fe^{2+}, the translocation of Fe^{2+}, which is more soluble, and the precipitation as $Fe(OH)_2$. Evidence against this mechanism of Fe eluviation is: (i) it does not account for the apparent overall similarity in the eluviation of Fe and Al in many Spodosols, and (ii) many coarse-textured Spodosols are saturated with water for only short time periods (reducing conditions). Oxidation of Fe^{2+} to Fe^{3+} and deposition as ferric hydroxide ($Fe(OH)_2$) occur under oxidizing conditions in the spodic horizon. Though such a mechanism may be operative in some soils, it is not likely to explain the development of a spodic horizon in all Spodosols.

III. Translocation and precipitation of Fe and Al due to low pH, i.e., acid weathering: Acid weathering of Al^{3+} (and iron) from the E horizon could account for eluviation of aluminum but low pH values (<= 4) are a prerequisite for this mechanism, which are commonly not found in many Spodosols.

IV. Translocation of sols: Movement of Al and Fe as hydrous oxide sols protected from flocculation by sols of opposite charge

IV. Translocation of sols: Movement of Al and Fe as hydrous oxide sols protected from flocculation by sols of opposite charge, such as humus or silica sols. However, organic matter is generally abundant in such soils and it is probable that the dissolved Al and Fe are complexed with humid substances. Flocculation of organic matter sols-colloidal humified organic matter might move as a negatively charged sol through the E horizon and be flocculated in the spodic horizon by cations. Evidence against this hypothesis is: (i) some spodic horizons are very poor in exchangeable cations, and (ii) most of the organic matter in many spodic horizons is fulvic acid, which forms true dilute aqueous solutions.

V. Formation of allophane / imogolite: Another hypothesis favors independent accumulation of Fe and Al in the subsoil either in-situ formation of short range order aluminosilicate minerals (allophane, imogolite - amorphous character) or translocation of these pedogenically-formed minerals from surface horizons to the subsoil. Organic matter is assumed to accumulate independently.

12.12.3) Properties

Spodosols are characterized by the presence of a spodic diagnostic horizon, which represents a subsurface accumulation of soil organic matter (SOM) with aluminum and / or iron sesquioxides (the products of podzolisation). The general concept of a spodic horizon is: An illuvial horizon containing active amorphous material and organic matter and Al with or without Fe. The phrase 'amorphous material' refers to material that has high cation-exchange capacity, large surface area, and high water retention. There are four classes of spodic horizons: friable, cemented, nodular, and placic. The friable spodic horizon shows the highest porosity, low resistance to root penetration, and highest hydraulic conductivity compared to the other spodic horizons. The cemented, nodular, and placic spodic horizons are characterized by high resistance to root penetration and low hydraulic conductivity, which enforce (temporary) ponding in slight depressions, surface runoff, and a decrease in infiltration. A placic horizon is a thin (usually 2-10 mm), black to dark-reddish pan cemented by iron, by iron and manganese, or by iron-organic matter complexes, which is relatively impermeable to water and plant roots. They occur in layered material (e.g. placic horizons that transgresses subhorizons) or in non-layered material of relatively uniform particle-size distribution (e.g. placic horizons within the B horizon). Placic horizons are usually associated with perudic to aquic soil-moisture regimes in coastal regions. Ortstein is a cemented layer by amorphous (Al, Fe)-organic complex material. The cementation may be either continuously or discontinuously in nodules from a few cubic centimeters to a cubic meter in volume. In ortstein horizons, amorphous material coats and joins the skeletal grains and partially fills intergranular spaces. The development of ortstein is favored by low nutrient supply, high water table and associated shallow rooting of plants, low activity of microflora and fauna.

Spodic horizons have the following charactersitics:

- >= 2.5 cm thick
- >= 85 % spodic materials
- not part of an Ap horizon
- pH <= 5.9

- organic carbon >= 0.6 %

One or more of the following:

- Strong color - hue 7.5 YR or redder; values and chroma (moist) <= 4

- A weaker color but accompanied by (i) ortstein in >= 50 % of the pedon, (ii) >= 10 % cracked coatings of organic matter and sesquioxides on sand grains, (iii) at least 0.50 % oxalate extractable aluminum plus one-half iron and less than half that amount in an overlying horizon, or (iv) an optical density of the oxalate extract (ODOE) of 0.25 and less than that value in an overlying horizon.

One or more of the following combinations of horizons may be recognized as spodic horizons in the field:

- Bh: OM accumulation

- Bs: Sesquioxides of Al and Fe

- Bhs: Mixture of the above

These horizons are typically associated with an bleached (gray to gray light color) E horizon (albic horizon), although this may be eroded or indistinguishable because of mixing with the A horizon by ploughing. Below the spodic horizon there may be a fragipan or another sequum that has an argillic horizon.

The development of spodic amorphous pellets common in the upper part of the spodic horizon may be due to the removal of polygonally cracked coatings from the surface of sand grains, i.e., monomorphic organic matter results of dissolution and precipitation of humified organic matter. Destruction of the pellets as soil development continues would leave essentially uncoated sand grains, an E horizon. Another hypothesis for the development of amorphous pellets ist that they are fecal pellets of soil fauna, i.e., polymorphic organic matter is of biological origin.

Typically, the horizons (O, A, E, Bh, Bs, or Bsh, C) in Spodosols are very pronounced and the width of the boundaries are abrupt. There are Spodosols with extremely thick E and Bsh horizons (several meters thickness).

Organic matter dominates the microfabric of many spodic horizons. It includes fresh to partly decomposed plant root fragments and amorphous organic matter in various forms: (i) polymorphic, i.e., discontinuous mass with variable color and density: Pellets of polymorphic organic matter, root remains, and elements of fungi may occur in intergranular spaces as loose aggregates; (ii) monomorphic, i.e., continuous mass with uniform color and density: Smooth polygonally cracked, coatings on skeletal grains and bridges between them and discrete aggregates in intergranular spaces. The organic components vary widely in size, concentration of functional groups and solubility and they include low molecular weight organic acids as well as humic acids. The silt and clay in sandy spodic horizons may occur almost entirely as coatings on skeleton grains. These cutans may be impregnated by and coated with monomporphic (Al, Fe)-organic complex material. Some spodic horizons that are relatively rich in silt and clay have a spongy fabric consisting of poorly defined aggregates of organic matter, silt and clay.

Most Spodosols show a sandy to loamy soil texture with few clay-sized silicates. Their particle-size class is mostly sandy, sandy-skeletal, coarse-loamy, loamy-skeletal, or coarse-silty. Typically, bulk density is lower in the upper soil horizons compared to the C horizon (e.g. in a Spodosol of the Laurentides soil in Canada: E: 1.0, Bh: 0.8, Bs: 1.4, C: 1.9 g/cm^3 - Wilding et al., 1983).

In most Spodosols the exchangeable bases are low and the pH-dependent exchange capacity of the B horizon is high. Spodosols with appreciable amounts of Al have large capacity to fix P, which is associated with the properties of the OM-sesquioxide complex in the spodic horizon.

12.12.4) Classification

Aquods: Aquods are the Spodosols of wet locations, characterized either by a shallow fluctuating water table or an extremely humid climate. They show a histic epipedon or redoximorphic features in the upper 50 cm. If the soil temperature regime is mesic or isomesic or warmer, most of them have a nearly white albic horizon thick enough to persist under cultivation or, in the wettest Aquods, a black surface horizon resting on a dark reddish brown spodic horizon that is virtually free of iron. Others have a placic horizon or a duripan, or are cemented by an amorphous mixture of sesquioxides and organic matter. The Aquods that do not have a placic horizon normally have a transitional horizon between the albic horizon and the spodic horizon, a feature virtually unique to these soils. Aquods have formed mainly in sandy materials of Pleistocene age. They may have any temperature regime. Water-loving plants of a wide variety, ranging from sphagnum in cold area to palms in the tropics, grow on these soils. These soils occupy local depressions or large areas of low relief and a high water table.

Cryods: Cryods are the Spodosols of high latitudes and/or high elevations that have a cryic soil temperature regime. Spodosol-like soils with pergelic soil temperature regimes are proposed to be classified as Spodi- great groups of Gelisols. Many Cryods have formed in volcanic ash or glacial drift, and some in residuum or colluvium on mountain slopes. They commonly have an O horizon over a very thin or intermittent albic horizon, which overlies a well-developed spodic horizon. Some have a placic horizon, ortstein, or other cemented soil layers within 100 cm of the soil surface. In many Cryods, the organic-carbon content in the upper part of the spodic horizon is relatively high. Vegetation is mostly coniferous forest or alpine tundra. In the United States they occur mostly in southeast Alaska and in the mountains of Washington and Oregon.

Humods: Humods are the relatively freely drained Spodosols that have a large accumulation of organic carbon in the spodic horizon (>= 6 % organic carbon). They have either a thin, intermittent or a distinct, continuous albic horizon over a spodic horizon, which in its upper part is nearly black and has a reddish hue. The hue normally becomes yellower with depth. Humods are derived predominantely from Pleistocene or Holocene sediments. In the United States they may have developed mainly under coniferous forests. In western Europe they are common in areas of sandy materials, where heather (Calluna vulgaris) is, or used to be, a dominant plant. In most tropical regions most Humods have supported a rain forest. The soils of this suborder are not extensive in the United States. They are known to occur in the Pacific Northwest, mostly in small areas, and my exist in the Southeast.

Orthods: Orthods are the relatively freely drained Spodosols that have a horizon of accumulation containing aluminum, or aluminum and iron, and organic carbon. They have formed predominantely in coarse, acid Pleistocene or Holocene deposits under mostly coniferous forest vegetation. Orthods normally have an O horizon, an albic, and a spodic horizon, and they may have a fragipan. Some of these soils, however, have been mixed by roots of falling trees or by animals and have a very thin albic horizon or none. Under cultivation the albic horizon is very commonly mixed with part of the spodic horizon. In the United States, the moisture regime of Orthods is predominantely udic, but a few have a xeric regime. Their soil temperature regimes range from frigid to hyperthermic. The Orthods are extensive in the southeastern United Staes, the Northeast, the Great lakes states, and the mountains of the West. Orthods are the most common Spodosols in the northern parts of Europe.

Several characteristics are considered to define Spodosols on great group and subgroup level:

Spodosols with a placic horizon are defined on the great group and subgroup level (e.g. Placaquods, Placic Cryaquods). The same is true for soils with a duripan (e.g. Duraquods, Duric Cryaquods) or a fragipan (e.g. Fragiaquods, Fragic Haplorthents).

If andic soil properties such as low bulk densities but high water-retention capabilities are present the denotion 'Andic' is used (e.g. Andic Cryaquods, Andic Haplohumods).

The soil moisture regime is used to define 'Aquic' (redoximorphic features in one or more horizons within 75 cm of the mineral horizon, and also aquic conditions for some time in most years) (e.g. Aquic Duricryods) and 'Oxyaquic', which are soils saturated with water, in one or more layers within 100 cm of the mineral soil surface, for 1 month or more per year in 6 or more out of 10 years (e.g. Oxyaquic Duricryods). Spodosols which show episaturation are denoted by 'Epi' (e.g. Epiaquods).

Spodosols with a spodic horizon 10 cm or more thick in 50 percent or more of each pedon are differentiated as 'Entic' (e.g. Entic Cryaquods, Entic Haplocryods).

Spodosols with an argillic or a kandic horizon within 200 cm of the mineral soil surface are denoted as 'Alfic' (e.g. Alfic Alaquods) or 'Ultic' (e.g. Ultic Alaquods).

Shallow Spodosols are differentiated by using 'Lithic' (e.g. Lithic Cryaquods).

Epipedons are used for the differentiation of Spodosols on subgroup level: Histic epipedons (e.g. Histic Alaquods), ochric epipedons (e.g. Aeric Alaquods), plaggen epipedons (e.g. Plaggeptic Fragiaquods), or umbric epipedons (e.g. Umbric Epiaquods).

Soil texture is used to define 'Arenic' Spodosols, that have a sandy or sandy-skeletal particle-size class throughout a layer extending from the mineral soil surface to the top of the spodic horizon at a depth of 75 to 125 cm (e.g. Arenic Alorthods).

12.12.5) Distinguishing Characteristics

Within a given landscape, distribution of Spodosols may be fairly continuous, or it may be spotty.

The definition of Spodosols which require a spodic horizon but not necessarily an eluvial horizon (albic horizon) distinguish

The definition of Spodosols which require a spodic horizon but not necessarily an eluvial horizon (albic horizon) distinguish Spodosols from Podzols.

The separation between Spodosols and Andisols is difficult, because aluminosilicates and organo-metallic complexes occur in the B horizons of soils of both orders.

Low temperatures and high water table favor maintenance of a relatively high content of organic matter in the spodic horizon. If accumulation of organic matter becomes more pronounced Histosols form. For example, the expansion of bogs by lateral growth of sphagnum may bury Spodosols under Histosols in the taiga of Canada.

Soils with an very thick (>= 200 cm) albic horizon overlying a spodic horizon are excluded from the Spodosol order and grouped with the Entisols or Inceptisols. For example, where parent material is sandy and spodic horizons may lie at a depth of several meters Quartzipsamments occur. Some of the very deep spodic horizons may be buried, but it seems likely that others have formed at great depths because the overlying soil materials have very little iron and aluminum that could precipitate the organic carbon.In some the source of aluminum may be the ground water.

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12.13) Ultisols

Summary:

- Vegetation: forest
- Climate: occur in any soil temperature regime
- Soil moisture regime: precipitation > evapotranspiration, xeric to aquic
- Major soil property: low base saturation
- Diagnostic horizons: argillic, kandic, albic
- Epipedon: ochric (umbric, mollic)
- Major processes: leaching, eluviation, illuviation
- Characteristics: low base status soils

12.13.1) Environmental Conditions

Climate: Ultisols are formed in climatic regions, where precipitation exceeds potential evapotranspiration during some periods each year. Also, the precipitation amount has to exceed the water storage capacity of the soil for some time of the year to allow water to percolate through the soil. This is essential to maintaining the low base status. Ultisols are found in tropical areas, where they tend to have somewhat finer textured E horizons, containing more organic matter and iron, than do the majority of Ultisols formed in temperate climate. Ultisols also may form in frigid soil temperature regimes. Xeric, perudic, udic, ustic, and aquic soil moisture regimes are present in various Ultisols.

Vegetation: Many Ultisols are formed under forest vegetation (e.g. mixed hardwood, pine, oak, hickory forest) although savannah or even swamp vegetation is possible. Because of their low base status most Ultisols are used for timber production but they are also used in agriculture, where liming and fertilization is important to decrease acidity and incease soil fertility. Where adequate agricultural management is applied these Ultisols are quite productive.

Relief: There are no limitations for relief where Ultisols might form. They may occupy hillslopes or level upland areas. The position they occupy is controlled by the relationship between geomorphology and other factors of formation and the resulting rates and degree of expression of pedogenic processes.

Parent Material: Common parent materials for the development of Ultisols contain few basic cations such as siliceous crystalline rocks (e.g. granite) or sedimentary material that is relatively poor in bases (e.g. highly weathered coastal plain sediment). Most of geologically old landscapes are covered by parent material rich in silica but poor in bases. There are some Ultisols formed in parent material with higher base status and less weathered material (e.g. volcanic ash, basic ignenous or metamorphic rocks). Rapid leaching of bases can occur where precipitation amounts are high to form Ultisols.

Time: Time periods involved in development of Ultisols depend on other factors of soil formation and the rate of specific pedogenic processes. A Pleistocene or older age is assigned most parent materials where Ultisols occur. The geologic age of parent materials, however, serves only to fix an absolute maximum on possible periods of time involved in soil formation. The actual time periods involved may be, and generally are, much less.

12.13.2) Processes

Many Ultisols develop from parent material that initially contain appreciable quantities of weatherable minerals. Mineral components released through weathering of these materials are susceptible to leaching.

Eluviation (translocation or leaching of clays) and illuviation (precipitation of clays) are major processes which form Ultisols. The upper soil profile is depleted by clays and lower soil horizons enriched in clays, i.e., an argillic or kandic diagnostic horizon is formed. Fine clays are more likely to be translocated compared to coarse clays. Also newly formed clay is more likely to move in percolating water than is clay coated with humic substances. In Ultisols the accumulation, decomposition and humification of organic matter in the topsoil is limited thus less organo-mineral complexes are formed, which increase the probability of eluviation and illuviation. The specific mechanisms of mobilization, translocation and deposition of clays can be explained by the following model: Clays are suspended by dispersion and moved downward with percolating water. Redeposition results from the effect as water is withdrawn by capillarity into the soil leaving the suspended clays as coatings on the surface of peds. Other particles, such as sesquioxides and organic matter may also be translocated in this manner. Only limited leaching is required to form Ultisols in acid parent materials containing few weatherable minerals. If the parent material is rich in bases extensive leaching over a long time is necessary to form Ultisols. Most of the Ultisols share the common characteristic of complete alteration of weatherable primary minerals into secondary minerals and oxides. Granite and other siliceous parent materials, slowly permeable materials, fluctuating water tables, and low-lying landscape positions favor kaolinite formation. Clay minerals found in Ultisols are mainly kaolinite and gibbsite as well as some 2:1 clay minerals.

It has been postulated that many Ultisols formed on geologically old landscapes do not have clay skins in the argillic or kandic horizon because the lessivage process is not active in soils with low weatherable mineral content, although it may have been more active during earlier stages of pedogenesis. The accumulation of clays in the B horizon is probably also a result of in situ weathering. With increasing depth below the soil surface, clay content is probably influenced less by processes of translocation and more by parent material and weathering. Argillic horizons increase with time and with increasing contents of silt and san-size resistant minerals in the parent materials. Argillic horizons may develop upward or downward in the solum and can be either constructive, destructive, or possibly 'equilibrium' develpment stages.The zone of illuviation is normally an argillic horizon but may be a fragipan that meets the requirements of an argillic horizon or has thick argillans.

There is a coexistence between lessivage and podzolization in Ultisols. Podzolization is the downward movement of sequioxides and organic components from the A and E horizons to the argillic or kandic horizon. The soluble ferrous iron forms (Fe^{2+}) at the sites of eluviation, and the insoluble ferric iron forms (Fe^{3+}) at the sites of illuviation. Translocation of Fe may occur as independent finely divided Fe-oxides, Fe-oxides attached to clays, clay-Fe-organic complexes, and soluble Fe-organic complexes.

The major process for the formation of plinthite requires appreciable periods of time in soils having adequate supplies of iron together with alternating oxidizing and reducing conditions associated with water tables that fluctuate through a limited segment of the solum for long periods during the year.

Accumulation, decomposition and humification are minor processes to form Ultisols. Most Ultisols exhibit a thin organic matter darkened surface layer.

12.13.3) Properties

Generally, an ochric epipedon and an argillic or kandic diagnostic horizon is found in Ultisols. In some Ultisols there are umbric or mollic epipedons. Most Ultisols are formed in weathered parent rock thus the subsurface horizons are underlain by a saprolite zone. A major characteristic of Ultisols is low base saturation throughout the soil profile with slightly higher base contents in the upper soil horizon due to biocycling. The low base saturation status is mainly due to formation in parent material high in silica but low in bases. In some soils, the low base status results from intense leaching of parent material initially high in content of weatherable minerals, while in others, a low base status and small quantities of weatherable minerals were initial parent material characteristics. Typically, the cation exchange capacity (CEC) is low with slightly higer CEC in the upper horizon due to biocycling of nutrients. In many Ultisols there are continuous losses of bases through leaching and erosion, therefore, the CEC remains low. In poorly drained Ultisols, such as the Umbraquults, the base content is slightly higher than in typical Ultisols. Abrupt decreases in base saturation are frequently associated with plinthite, fragipans, or other zones that are saturated for prolonged periods.

Associated with low base (low nutrient) content is a high soil acidity. Surface horizons rarely have pH values less than 5.0 or greater 5.8. In general, the pH values decrease with depth to a minimum of 4.0 to 5.5 in the argillic horizon. In highly weathered and leached Ultisols a decreasing pH is evident throughout the solum.

In most Ultisols organic matter is restricted to the light-colored ochric epipedon. This can be attributed to high decomposition rates by aerobic micro-organisms under warm climates and free soil-drainage. Most of the annual increments of added organic residues are on the surface, where the oxygen and nutrient status of Ultisols are most suitable for high populations of micro-organisms. Organic matter content and thickness of the surface horizon increase in most Ultisols with decreasing internal soil drainage and aeration and umbric epipedons can form under these conditions. Ultisols with high organic matter are typified by the Humic taxa. The organic matter content found in many Ultisols is low compared to other soil orders such as Mollisols or Alfisols.

Clays in Ultisols are usually of the 1:1 type (kaolinite) or gibbsite - there are less clays of the 2:1 type. Therefore, the cation exchange capacity and water holding capacity is relatively low in most Ultisols. These limitations can be overcome by the application of lime to decrease acidity and fertilizers to add bases to the soil but Ultisols are commonly not as productive as Mollsiols or Alfisols. Clay content increases regularly from A, E or upper B horizons to a maximum in the upper part of the argillic horizon, then decreases regularly with depth into the C horizon.

Iron oxides, released from other minerals through weathering or inherited as such from the parent material, are important pedogenic and taxonomic indicators in Ultisols. Goethite is the dominant crystalline form in most Ultisols and commonly associated with lesser quantities of hematite, maghemite, and magnetite. The amounts of hematite are generally greater in Ultisols developed from basic rocks and are more abundant in tropical then temperate regions. This accounts for the red color in well-drained tropical Ultisols compared to other rgions. The red or yellow colors found in the argillic horizon and underlying materials in many Ultisols are due to iron oxides. In most Ultisols, various proportions of the soil are comprised of reddish and grayish or light-colored mottles. This condition is normally associated with segregation of Fe-oxides by alternating oxidation and reduction. Reduction forms relatively soluble Fe^{2+} which may migrate to more oxidizing locations before reoxidization or reoxidize and precipitate in situ on existing Fe^{3+} compounds. Repetitions of the cycle result in development of zones with high and low free iron contents corresponding to the reddish and grayish colors. The behavior of Mn in oxidizing and reducing environments is analogous to that of Fe. Through continued segregation and concentration of oxides by alternating oxidizing and reducing conditions plinthite or fragipans are formed. Plinthite are humus-poor but sequioxide-rich horizons that hardens irreversibly to ironstone hardpans or aggregates with repeated wetting and drying. When sesquioxide-rich features are found on the soil surface or exposed in a cut bank, they are commonly called 'laterite'. It is assumed that the formation of plinthite is associated with a seasonally fluctuating water table and the translocation of sesquioxides. The consequence of plinthite is impeded drainage and waterlogging. In Soil Taxonomy 'plinthite' is used for characterization of Ultisols when > 5 % of the volume of a soil horizon is occupied by plinthite. Fragipans form in similar environmental settings and fragipans and plinthite can occur in the same soil. Fragipans are layers of high bulk density, brittle when moist, and hard when dry. Many fragipans in Ultisols are associated with either, or both, lithologic or chronological discontinuities in the parent material. It has been postulated that many fragipans in Ultisols are a result of pedogenic processes, i.e., the precipitation of silica, clays, and/or sequioxides, which result in high bulk densities. The brittlesness is attributed to binding of amorphous material and the formation of aluminosilicate binding agents.

A typical sequence in an Ultisol profile could be characterized by a distinct E horizon that thickens upward into the overlying argillic and downward into the fragipan, such as A, E, BE, Bt, BC, and C horizons. The A horizons are commonly less than 15 cm thick with (dark) grayish-brown colors and weak or moderate granular structure. E horizons are comparable in thickness and have a weak structure or are structureless and may meet the criteria set for albic horizons. Chromas of 3 to 5 and values of 4 to 6 are common in most E horizons. Colors of the B horizon are generally 10YR or redder hue with values of 4 to 6 and chromas 6 to 8. The structure of the B horizon is typically moderate, medium subangular blocky and becomes weaker and coarser with increasing depth. The underlying C horizon has weaker and coarser structure or is structureless. Colors are less red and clay contents lower.

12.13.4) Classification

The requirements to qualify as an Ultisols are:

- Low base saturation (< 35 %) at 125 cm below the top of the argillic horizon or 180 cm below the surface, providing there are no intervening lithic or paralithic contacts.

- Diagnostic features: Presence of an argillic or kandic horizon, i.e., a zone of accumulation of clays

The major requirements, an argillic horizon and low base status, may develop simultaneously or sequentially with either preceding the other.

A distinct E horizon is not required in Ultisols. Ultisols occupy extensive areas in the south-eastern United States, east central Africa, northeast India, southwest China, and northeastern Australia. There are 5 suborders in the Ultisol order, whereas soil moisture regime and organic matter are used to distinguish the suborders.

- Aquults: They are saturated with water at some period of the year or are artificially drained. Aquic conditions form redoximorphic features.

- Ustults: Ultisols formed in ustic soil moisture regime are classified as Ustults. Although moisture is limiting, it is seasonally available in adequate amounts for at least one crop per year.

- Humults: They have high organic matter contents but do not have other characteristics of wetness. Humults are found in Hawaii, eastern California, and Washington.

- Udults:Ultisols formed in humid regions, where dry periods are short are classifed as Udults. Their organic matter content is low. For short periods of time there might be a high water table in the solum but Udults do not show distinct redoximorphic features. For example, Udults extend from the east coast (Maryland to Florida) and beyond the Mississippi River Valley and are the most extensive soils in the humid southeast.

the most extensive soils in the humid southeast.

Xerults: Ultisols formed in xeric soil moisture regimes.

In Soil Taxonomy, the content and distribution of organic matter together with soil-drainage characteristics are definitive criteria for Humic, Umbric, and Sombric taxa. A sombric horizon is a subsurface horizon of illuvial accumulation of organic matter, which is not found under an albic horizon (e.g. Sombrihumults, Sombric Kandiudults). They are not known to occur in the U.S. and have been reported only in cool, moist, high plateau and mountain areas in intertropical regions. Organic matter in sombric horizons is not associated with large quantities of Al to the extent it is in spodic horizons. Umbric, i.e., the presence of an umbric epipedon is considered at subgroup level (e.g. Umbric Fragiaquults). Humic Ultisols show either an Ap horizon, or an A horizon 15 cm or more thick, that has a color value, moist, of 3 or less and a color value, dry, of 5 or less, which indirectly describes the presence of humus (e.g. Humic Hapludults).

Several soil moisture regimes are considered at sugroup level ranging from dry to wet conditons: Xeric (e.g. Xeric Kandihumults), aridic (e.g. Aridic Aridic Kandiustults), udic (e.g Udic Kandiustults), ustic (e.g. Ustic Kandihumults), and aquic (e.g. Aquic Paleudults).

The fragipan horizon is diagnostic for fragic great groups and subgroups in Ultisols (e.g. Fragiaquults, Fragic Paleudults, Fragic Hapludults). Soils that meet the fragipan criteria are common in the eastern part of the United States. Ultisols with a plinthic diagnostic horizon are, for example, Plinthquults, Plinthic Paleaquults.

In some Ultisols spodic characteristics are present (e.g. Spodic Paleudults), i.e., an illuvial accumulation of sequioxides and/or organic matter. It is suggested that the spodic horizon developed in a thick, sandy eluvial horizon of an existing Ultisol. Simultaneous formation and expression of argillic and spodic horizon characteristics are essentially mutually exclusive phenomena. Continued development of the spodic horizon should eventually result in either destruction of the argillic horizon or its translocation to a greater depth. Typically spodic horizons are found in the Spodosol order.

Ultisols in Vertic subgroups (e.g. Vertic Paleudults, Vertic Albaquults) do have appreciable shrink-swell capacities and extensive cracks can be observed in the B horizon during dry season. They develope in clayey sediment, for example, in Puerto Rico and the southeastern United States. A low weatherable mineral content in the non-clay fraction is considered essential to their development. Bases lost through leaching are not replenished by weathering and a low base saturation can develop in relatively short time periods.

Ultisols developed in volcanic ash or other pryoclastics are classified as 'Andic'. They have significant quantities of highly reactive allophane or similar amorphous aluminosilicate materials. Their bulk density is low (<= 1.0 g/cm^3) but they show high water-retention capabilities (e.g. Andic Kandihumults, Andic Kanhaplustults). Such soils can be found in Hawaii.

Soil texture is used to define 'Arenic' (soils that have a sandy or sandy-skeletal particle-size class throughout a layer extending from the mineral soil surface to the top of an argillic horizon at a depth of 50 to 100 cm) and 'Psammentic' (soils that have a sandy particle-size class throughout the upper 75 cm of the argillic horizon, or throughout the entire argillic horizon if it is less than 75 cm thick) (e.g. Arenic Paleaquults, Psammentic Rhodudults).

Ultisols with a soil color that have 50 percent or more chroma of 3 or more in one or more horizons between either the A or Ap horizon or a depth of 25 cm from the mineral soil surface, whichever is deeper, and a depth of 75 cm are defined as 'Aeric' (e.g. Aeric Paleaquults). Ultisols which show a red color are defined by 'Rhodic' (a hue of 2.5YR or redder; and a value moist of 3 or less; and a value dry no more than 1 unit higher than the value moist) (e.g. Rhodic Kandiudults).

Shallow Ultisols are defined as 'Lithic' (e.g. Lithic Kanhaplohumults, Lithic Haplustults).

Ultisols which are grouped as 'old soils' are denoted by 'Pale' (e.g. Palehumults, Palexerults). They are not allowed to have a densic, lithic, paralithic, or petroferric contact within 150 cm of the mineral soil surface. Other limitations to qualify for a Pale subgroup within the Ultisol order are texture changes or skeletans on the faces of peds.

12.13.5) Distinguishing Characteristics

Ultisols and Alfisols share the presence of argillic diagnostic horizons but the low base status of Ultisols is the primary characteristic differentiating them from most Alfisols. Most Ultisols are more highly weathered and acidic than Alfisols but generally Ultisols are not as acid as Spodosols.

The absence of an argillic horizon and the absence of an argillic horizon above an oxic horizon in Inceptisols and Oxisols, respectively, are the criteria used to distinguish them from Ultisols. To distinguish between Ultisols and Oxisols - there are still some weatherable minerals found in Ultisols compared to Oxisols. If base saturation < 35 %, a kandic horizon is present, and less than 40 % clay is found in the surface 18 cm the soil is classified as an Ultisol. In contrast, similar soils with more than 40 % clay in the surface are recognized as distinctive great groups of Oxisols.

Mollisols may occupy drier less leached positions, wetter positions, where leaching has been retarded and/or secondary enrichment with bases has occured. In areas with coarse-textured parent material, Spodosols may develop in low, poorly drained landscape positions with Ultisols on the better-drained sites. Histosols may develop in flat, depressional or poorly drained areas surrounded by Ultisols. Entisols can develop in association with Ultisols in very poorly drained areas or on steep rapidly eroding areas. Aridisols and Vertisols can occur in close proximity to Ultisols in areas where Ultisols adjoin arid climates. Inceptisols form on less stable landscape positions (steep slopes) and at higher elevations in mountainous areas or on floodplains (e.g. Fluvaquents). Soils associated with Ultisols are Psamments in areas of extremely sandy material.

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12.14) Vertisols

Summary:

- Vegetation: grassland, deep rooting tree species

- Climate: seasonal variations in precipitation and temperature; any soil temperature regime except pergelic
- Soil moisture regime: erratic soil moisture regime
- Major soil property: high clay content (predominance of 2:1 type expanding clay -> montmorillonite, smectite), high CEC, low permeability, slickensides, gilgai micro-relief, dark color of low chroma, medium to low organic matter content (0.5 - 3 %)
- Diagnostic horizons: cambic (argillic, natric)
- Epipedon: mollic
- Major processes: shrinking and swelling, pedoturbation
- Characteristics: stage of weathering relatively unadvanced or minimal, lack in horizon differentiation

12.14.1) Environmental Conditions

Climate: Vertisols occur in almost every major climatic zone. Australia with over 80 million ha has the largest occurence of Vertisols, where they are formed mainly in areas with aridic moisture regime, with less in ustic and xeric zones. Generally, the seasonal variations in precipitation and temperature, which favor the formation of smectitic clays as well as provide many of the physical attributes of these soils, would be considered as prerequisites for the formation of Vertisols. The variation in climatic conditions result in weathering of primary and secondary minerals during wet season, but encourage the accumulation of basic cations in the dry season. Areas where Vertisols are found are characterized by a period when the potential evapotranspiration exceeds precipitation (fry period). During periods with sufficient moisture deficit cracking occurs, although the intensity in cold temperature regions, such as Canada, is much lower than in the warmer regions. Generally, higher rainfall results in higher intensity of cracking, increased organic matter contents, and increased leaching of carbonates and salts.

Vegetation: Since it is known that Vertisols occur in a wide variety of climatic types, the natural vegetation associated with this soil order is equally variable. The natural vegetation types are, to a certain extent, limited by the soil properties such as the high clay content, shring-swell characteristics, and soil structure. Both climate and soil properties limit the vegetation types to grasses and slow-growing, deep-rooting tree species (e.g. Acacia). The main features of the natural vegetation in these soils are tolerance to drought, as well as development of deep roots to overcome root damage by a consequence of the annual cracking. Most Vertisols have has grassland or savanna vegetation as the native vegetation, but some had formed under forest. Present use of Vertisols comprise wheat, rice, cotton, and sorghum, pastureland in the the south of the United States. Vertisols in India are used for grain legume, oil seed crops, and cotton cultivated in a ridge and furrow system. In Australia most Vertisols are used for grazing by sheep and cattle or dry land agriculture. Large areas of Vertisols in Africa are largely un-utilized except for extensive grazing.

Relief: Two different scales should be examined (i) macro, and (ii) micro scale.

(i) Macro relief: Vertisols generally occur in areas with slopes not exceeding 5 % gradient, since at higher gradients soil erosion would occur. Often the level areas lack an integrated drainage network, hence infiltration is slow in these soils, which results in surface ponding.

(ii) Micro relief: Gilgai-relief. The development of gilgai-relief is due to shrinking and swelling of Vertisols and soil movement, i.e., the soil mass cannot re-occupy the original volume since surficial material has fallen into the cracks during dry season. As such, part of the soil mass is forced upwards forming the mounds (or knolls). The formation of a mound provides a locally preferred site for the further release of pressure, thereby perpetuating the formation of other mounds and depressions in an area.

Parent Material: Vertisols develop on a wide range of parent material including alluvial, colluvial and lacustrine deposits, marl and other calcareaous rocks, limestone, shales, igneous, metamorphic and volcanic rocks of basic nature. The materials that form Vertisols can be either allochtonous or autochthonous in origin. In most cases the materials are recently deposited and soil formation is still in the early stages. Vertisols may develop in situ from the parent materials. The smectites (clay minerals) in these soils could be derived from the original rock or form as a result of neogenesis or transformations from primary minerals. A high pH and high potentials of Si as well as Mg smectites develop, a process which is also favored by poor drainage conditions. Calcareous parent material or unconsolidated sediments which are dominantely basic in character and low in quartz favor the formation of Vertisols. Vertisols occupy approximately 1 percent of the land mass of the U.S. and are dominant mainly in Texas, Alabama and Mississippi. Those soils have developed on gentle slopes either in calcareous clay or in residuum weathered from soft, calcareous sedimentary rocks. Vertisols are known to develop on basalts in Australia, gneisses and sandstones in India, or glacio-lacustrine in Saskatchewan. The parent material although variable in origin, are rich in feldspars and ferro-magnesian minerals and yield clay residues on weathering. Where parent materials are not basic, alkaline earth elements can be added by seepage or by flood water.

Time: Most Vertisols develop on young landscapes but they may occur on old geomorphic surfaces. It is believed that the stage of weathering in Vertisols is relatively unadvanced or minimal.

12.14.2) Processes

Vertisols form under multiple genetic pathways which are complex. In general, soil forming processes that lead to the formation of Vertisols are those which control the formation and stability of smectites in the soil. However, subsidiary processes, such as fluctuations in the moisture status, accumulation of organic matter, carbonates, gypsum or soluble salts and acidification processes through leaching, result in the differences within the Vertisols.

The development of Vertisols requires conditions that ensure the formation and preservation of smectites. These clay minerals may form either in situ through the weathering and development of a solum (autochtonous Vertisols) or from a sediment which is composed of materials that can produce vertic properties (allochtonous Vertisols). The latter is geographically more extensive and occupies the lower parts of the landscape. The development of smectitic clays is favored by a high pH with sufficient Ca^{2+} and Mg^{2+} in the soil system. The presence of a relatively impermeable layer at some depth within the soil prevents the leaching of the various components needed to form smectites.

Shrinking and swelling cause shearing and consequently the formation of slickensides. This process is attributed to smectitic clays and alternations in dry and wet seasons. As a result of this process, Vertisols develop deep and wide cracks in a polygonal pattern.

Pedoturbation (churning) is a process which homogenizes the soil profile due to the infilling of the cracks by surficial material during dry season. The process in Vertisols is also called self-mulching or self-swallowing.

During the drying cycles, cracks develop, whereas on moistening, shear stresses form which result in the formation of slickensides and/or smoothened surface of sphenoids. Both features require the material to be in a plastic state. The lateral pressures developed in these soils are much greater than the vertical swelling pressures. Within the soil, the vertical component of the swelling pressures includes the weight of the overlying material. The moisture conditions above and below a point within the soil determines the net pressure and angle of shear. As such, the near surface horizon develop cracks and may have only a few slickensides since both the horizontal and vertical pressures are small (the net pressure being much lower than the sheat strength of the material). In deeper horizons, typically from 50 to about 125 cm below the surface, slickensides development is maximum. In these deeper layers, the net pressure is much greater than the shear strength of the material and soil movement occurs with swelling. Sphenoids develop as a result of the existence of much lower vertical and horizontal pressures in comparison to that needed for the development of slickensides. In the typical case, sphenoids would be found in between the surface horizon with cracks and deeper horizons with slickensides. Their development has been related to lower clay contents, as well as smaller proportions of smectitic clays in the colloidal fractions.

Clay translocation is not phenomenal in Vertisols, nevertheless, the presence of smectitic clays has all the conditions necessary for dispersion, translocation, and accumulation in subsurface horizons in Vertisols. In some Vertisols there is some evidence of illuviated clays in the lower soil profile, which is subjected to the least amount of pedoturbation. This process tends to obliterate all evidence of the illuviation process and it is unlikely that well-defined clay skins will be preserved, instead any translocated clay is probably engulfed in the matrix and/or slickensides as a result of shrink-swell processes.

Summary - Pedogenic Models for the Formation of Vertisols

(I) Pedoturbation Model (Self-Swallowing Model)

Prerequisite for the formation of Vertisols is the presence of expanding clays (smectites). After clay formation shrink-swell processes begin to operate. During the dry season the soil cracks. While the cracks are open, surface soil material falls into them due to wind, animal acitivity, or water erosion. On rewetting the clays hydrate and expand. As expansion takes place, the cracks close, but because of the 'additional' material now present in the lower parts of the profile, a greater volume is required and the expanding material presses and slides the aggregates against each other developing slickensides.

(II) Soil Mechanistic Model

This model is based on the failure along shear planes (slickensides) of plastic soil material when swelling pressures generated by hydration of clays exceed the shear strength of the soil material. Stress is relieved by an upward movement that is constrained by hydration of clays exceed the shear strength of the soil material. Stress is relieved by an upward movement that is constrained by the weight of the overlying soil material, resulting in a failure shear plane that is usually inclined at 10 - 60° above the horizontal. This model does not require that surface material falls into cracks. Instead, surface material is transported upward along the slickensides to produce the microknolls of the gilgai-relief. Once microrelief is established, soil processes are driven largely by small-scale variations in hydrology and microclimate, and less so by pedoturbation.

12.14.3) Properties

Five zones or horizons with distinct structural attributes may be recognized in Vertisols, although not all may be present in a particular profile and may not occur in a strictly ordered sequence.

- Zone 1: This zone is from the surface to approximately 25 cm or the plow layer if present. It is characterized by large prisms, up to 30 cm in width, that result from cracking. The material is hard or very hard when dry and the prismatic elements may part to coarse angular blocky elements.

- Zone 2: This zone is typically 10 to 30 cm thick and characterized by coarse angular blocky elements that may occur aggregated into discernable prisms. If overlain by a plow zone, it may represent a root restricting layer for agricultural crops.

- Zone 3: This zone may vary in thickness from 10 to over 100cm. Soil Taxonomy refers to the structural elements in this zone as 'wedge-shaped natural structural aggregates that have their long axis tilted 10 to 60 degrees from the horizontal'. These structural aggregates have an orthorhombic form, are generally 5 to 10 cm long along their long axis; and smooth or striated ped faces. Their mode of formation is related to the slickensides, which are characteristic of zone 4.

- Zone 4:This is the zone of slickenside formation and ranges from 25 to 100 cm in thickness. The term slickenside refers to a surface that has a polished and shiny appearence that also may be grooved or striated. The term does not refer to a soil structural element, which is a 3-D entity. In this zone the slickensides occupy areas ranging from 600 to 2000 cm^2. Their surface topography is not flat, but curved or slightly undulating. The net result of the inclined arrangement is to produce a set of intersecting slickensides arranged in a synclinal form. The deepest part of the syncline is between 50 and 125 cm below the surface, while the shallower arms may reach within 25 cm of the surface. The amplitude of the two arms represents the amplitude of the gilgai and may vary from about 3 m to more than 25 m. The thickness and expression of zones 2 &3 are a function of the depth at which the arms of the slickensides approach the surface.

- Zone 5: This zone underlies zone 4 or is directly below zone 3. It is subject to only slight moisture variation and is massive and may show accumulations of gypsum, carbonates and other translocated soluble salts.

Variations from the model profile is the rule rather than the exception. One or more of zones 2, 3 or 4 may be absent, but 'conceptually zone 3, 4 or both must be present for recognition as a Vertisol. The expression of zones 2, 3 and 4 will show considerable variation as a function of soil moisture content and variation in intrinsic soil attributes (variation in clay type and content), however their relative positions are usually sequential.

Generally, the clay content is very high in Vertisols and the dominant clay minerals are 2:1 type minerals (smectites, montmorillonites). These clay minerals have the outstanding feature to expand (swell) when wet and shrink when dry. Therefore, pronounced changes in volumes with changes in soil moisture result in deep cracks in the dry season and very plastic and sticky soil consistency when wet. Due to the high clay content of expanding character the cation exchange capacity of the whole soil is high. A high clay content is also associated with slow permeability but the water adsorption is high.

Slickensides are a pronounced characteristic of Vertisols. They are defined as polished and grooved surfaces produced by one soil mass sliding past another. The formation of slickenside features is related to swelling pressures which exceed the shear strength of the soil under overburden-pressure confinement. The shear strength of a soil is a function of cohesion plus the angle of internal friction, which is low in clay soils. The cohesion is a function of bulk density, clay content, clay mineralogy, and is inversely related to moisture content. Generally, lateral swelling pressures in soils are much larger than vertical swelling pressures, as the latter is substantially reduced by the overburden pressure. Maximum slickensides are between 50 and 125 cm depth, however, fewer slickensides are found at depths between 25 and 50 cm. At such depths both vertical and horizontal pressures are small. As the moisture changes become limited at 125 cm depth, slickensides become scarce below this depth. Shearing occurs at an angle of 30 to 50 degrees from the horizontal and it is dependent on moisture and the swelling pressures, which vary vertically, horizontally, and temporally. Slickensides can only form when the material is plastic. The slickensides (stress cutans) differ markedly from clay skins (argillans) which occur on the ped surfaces resulting from clay translocation. The latter have sharp outer and inner boundaries with distinct extinction patterns and are often finely layered (laminar fabric). The relatively small slickensides developed by pedogenesis must not be confuse with large slickensides of the substratum which in alluvial and lacustrine sediments is a feature of the parent material.

The organic matter content is generally low (0.5 - 3 %) in spite of the usual dark soil color. Complexation or chelation of organic colloids to clay minerals of the smectite group probably darkens the mineral. Some of the dark color may also be related to presence of manganese oxides. The dark black color may be also due to the parent material (e.g. Vertisols derived from basalt). The Chrom great groups of Vertisols are brownish in color and typically have small amounts of montmorillonites. These great groups typically have large amounts of iron oxyhydroxides and are well-drained.

Kankars (carbonate glaebules or nodules) are basically lime concretions that are found in Vertisols. Many Vertisols are formed in calcareous parent material and have kankars throughout the profile. In deeper horizons, it is also common to find calcic horizons. Drying, in the presence of Fe and Mn, results in the formation of hard concretions.

The structure of Vertisols is almost a temporal characteristic. The size, shape, grade, and consistence of the structural elements are all related to the moisture conditions at the time the soil is inspected. The depth at which the different structural elements are expressed may also be a function of moisture conditions in different parts of the profile. Ideally, structural assessments should be made under different moisture conditions. Often Vertisols show an angular blocky structure (wedge-shaped aggegates).

Typical microrelief features are knolls (mounds) and basins (depressions) in a Vertisol landscape. The basins are wetter than the knolls due to moisture release from the cracks and water ponding during wet periods. They exhibit higher organic matter contents and are often more saline than the microknolls. The knolls are drier, have a higher calcium carbonate content and are in the erosional positions. Minibasins and microknolls show a repetitive but irregular pattern within a Vertisol landscape with distances of about 3 to 10 m between the knolls. The topography related to Vertisols is called 'Gilgai micro-topography'. Various forms of gilgai have been reported: round, mushroom, tank, wavy, lattice, stony, and depressional. The form is related to landscape shape, clay content and type, and soil moisture regime. A fine, angular blocky structure, described by some as 'nutty' may develop in surfaces that have a very high montmorillonitic clay content. In the dry season they show a very hard consistence and appear as loose gravel strewn on the surface. In previous classification systems these soils were called Grumosols.

Most Vertisols have a mollic epipedon and a cambic diagnostic horizon, but some have other diagnostic subsurface horizons, including argillic or natric.

12.14.4) Classification

The requirements to qualify for a Vertisol are the following:

- Clay content of at least 30 % to a depth of at least 50 cm, or a lithic or paralithic contact, duripan, or a petrocalcic horizon if shallower
- Cracks that open and close periodically
- Evidence of soil movement (e.g. slickensides, wedge-shaped aggregates)
- Any soil temperature regime, except pergelic (i.e., Gelisols)
- Soil moisture regime must be erratic to allow for cracking in dry season and swelling in wet season

Gilgai surface topography is not considered as a requirement to meet a Vertisol. Cultivation practice may erase gilgai microtopography.

Six suborders are recognized in the Vertisol order. They are differentiated by aquic conditions, soil moisture regime, and on the cracking characteristics of the soil. Note that although the formative elements for soil moisture regimes are used in naming Xererts, Torrerts, Usterts, and Uderts, the names do not necessarily mean that the soils have those soil moisture regimes.

- Aquerts: Vertisols which are subdued aquic conditions for some time in most years and show redoximorphic features are grouped as Aquerts. Because of the high clay content the permeability is slowed down and aquic conditions are likely to occur. In general, when precipitation exceeds evapotranspiration ponding may occur. Under wet soil moisture conditions iron and manganese is mobilized and reduced. The manganese may be partly responsible for the dark color of the soil profile.

- Cryerts: They have a cryic soil temperature regime. Cryerts are most extensive in the grassland and forest-grassland transitions zones of the Canadian Prairies and at similar latitudes in the Soviet Union.

- Xererts: They have a thermic, mesic, or frigid soil temperature regime. They show cracks that are open at least 60 consecutive days during the summer, but are closed at least 60 consecutive days during winter. Xererts are most extensive in the western United States, primarily in California.

Torrerts: They have cracks that are closed for less than 60 consecutive days when the soil temperature at 50 cm is above 8° C. These soils are not extensive in the U.S., and occur mostly in west Texas, New Mexico, Arizona, and South Dakota, but are the most extensive suborder of Vertisols in Australia.

Usterts: They have cracks that are open for at least 90 cumulative days per year. Globally, this suborder is the most extensive of the Vertisols order, encompassing the Vertisols of the tropics and monsoonal climates in Australia, India, and Africa. In the U.S. the Usterts are common in Texas, Montana, Hawaii, and California.

Uderts: They have cracks that are open less than 90 cumulative days per year and less than 60 consecutive days during the summer. These are the Vertisols of the Gulf Coastal Plain and the Black Belt in Mississippi and Alabama.

Great groups are differentiated by subsurface diagnostic horizons (e.g. salic, calcic, natric, gypsic horizons), the presence of a duripan (e.g. Duraquerts, Durixererts), organic carbon content (e.g. Humicryerts), or reaction (electrical conductivity is less than 4 dS/m and pH in 1:1 water of 5 or less in 25 cm or more within top 50 cm - e.g. Dystrusters, Dystraquerts).

Several soil moisture regimes are considered at sugroup level ranging from dry to wet conditons: Xeric (e.g. Xeric Epiaquerts), aridic (e.g. Aridic Epiaquerts), udic (e.g Udic Haplusterts), ustic (e.g. Ustic Dystraquerts), and aquic (e.g. Aquic Dystrusterts, Aquic Salitorrerts).

Soil color is used to differentiate the 'aeric' subgroup of Vertisols. Soils that have in one or more horizons between either an Ap horizon or a depth of 25 cm from the mineral soil surface, whichever is deeper, 50 percent or more colors as follows: (i) a hue of 2.5 of redder and either (ii) a color value, moist, of 6 or more and a chroma of 3 or more; or (iii) a color value, moist, of 5 or less and a chroma of 2 or more; or (iv) a hue of 5Y and a chroma of 3 or more; or (v) a chroma of 2 or more, and no redox concentrations (e.g. Aeric Endoaquerts). Soil color is used also to differentiate the 'chromic' subgroup of Vertisols. The chromic characteristic encompass soils that have, in one or more horizons within 30 cm of the mineral soil surface, 50 percent or more colors as follows: (i) a color value, moist, of 4 or more; or (ii) a color value, dry, of 6 or more; or (iii) a chroma of 3 or more (e.g. Chromic Epiaquerts).

Shallow Vertisols are classified using the designation 'leptic' (soil with a densic, lithic, or paralithic contact within 100 cm of the mineral soil surface) or 'lithic' (e.g. Leptic Salaquerts or Lithic Haploxererts).

Vertisols which are low in clay content are differentiated as 'entic'. To meet the 'entic' designation the Vertisol must have a layer 25 cm or more thick that contains less than 27 percent clay in its fine-earth fraction and has its upper boundary within 100 cm of the mineral soil surface (e.g. Entic Salaquerts, Entic Haplotorrerts).

Soils are defined by the designation 'halic' if their salt content is high. They must meet the following criterion : throughout a layer 15 cm or thicker the electrical conductivity must be at least 15 dS/m or more (1:1 soil:water) for 6 or more months per year in 6 or more out of 10 years (e.g. Halic Durixererts). Vertisols with a high sodium content are classified as 'sodic' (e.g. Sodic

Durixererts). They must have an exchangeable sodium percentage of 15 or more (or a sodium adsorption ratio of 13 or more) for 6 or more months per year in 6 or more out of 10 years.

12.14.5) Distinguishing Characteristics

Soils at higher elevations and on steeper slopes formed in the same parent material as Vertisols are classified as Inceptisols and Alfisols and they may have vertic properties. In a catenary association Alfisols may occur on the top of the slopes - Entisols, Inceptisols, and Alfisols with vertic properties on the erosional hillslope positions - and Vertisols on the lower slopes and in the depressions. The main associated soils formed in calcareous parent material are Ustolls, Aqualfs in the less calcareous clays, and soils in vertic subgroups of Ustolls and Aquolls on nearly level slopes. With advancement of leaching and the formation of an argillic horizon, the soil would evolve into Alfisols (e.g. Vertic Hapludalfs). Leaching also promotes the destruction of smectites, i.e., the vertic properties of the soils are destroyed and Alfisols are formed. A number of Inceptisols, Entisols, Alfisols, Mollisols, Ultisols, and Aridisols intergrade to Vertisols at the subgroup level. These soils have vertic characteristics such as cracking, slickensides or wedge-shaped aggregates, but not enough to be Vertisols.

Further Reading

Ahmad N., and A. Mermut. 1996. Vertisols and Technologies for their Management. Development in Soil Science 24. Elsevier, New York.

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12.13) Summary / Orders

12.13.1) Soil Orders - Parent Material

Alfisols:

High to medium base status soils with argillic horizons

· Most Alfisols are present on relative old landscapes (beginning Holocene or older) whereever the supply of primary minerals is plentiful

· They also occur on glacial drift

· A wide variety of clay minerals ® high cation exchange capacity

Andisols:

Soils with andic soil properties

· Pyroclastic deposits (volcanic ejecta) such as ash, pumice, cinders, and lava

· Characteristic:

· vitric material or volcanic glass, which are dominated by amorphous, short-range-order minerals

· low bulk density < 0.9 g/cm3

· Allophane and imogolite are common early-stage residual weathering products of volcanic glass

Aridisols

Soils of dry regions

· Wide variety of parent material:

· Glacial drift

· Crystalline rocks

· Fluvial and eolian deposits (unconsolidated material)

· Parent material rich in sand-sized particles

· Gypsiferous material formed from sedimentary rocks

· Limestone

Entisols:

Recently formed soils

· Land surfaces that are very young (alluvium, colluvium, mudflows)

· Extremely hard rocks

· Sandy parent material

· Disturbed material (e.g. mined land, highly compacted soils, toxic material)

· Transitions between 'soils' and 'not soils'

Gelisols

Soils formed in cool climate (pergelic temperature regime)

· Any parent material

· Often: Glacial drift

Histosols

Organic soils

· Organic material (e.g. peats, bogs, wetlands)

Inceptisols

Embryonic soils with few diagnostic features

· Glacial deposits

· Recent deposits in valleys or deltas

· Most Inceptisols occur on geologically young sediments (e.g. alluvium, colluvium, loess)

· Parent materials which are highly calcareous or resistant to weathering inhibit soil development but favor the development of Inceptisols

Mollisols:

Grassland soils of steppes and prairies (base rich soils)

· Deposits and landscapes with a wide range of ages

· Many Mollisols are formed on deposits associated with glaciation (unconsolidated quaternary materials) - calcareous rich aolian deposits supported the formation of Mollisols

· However, in other areas they develop in residuum weathered from sedimentary rocks

Oxisols:

Low-activity soils

· Highly weathered transported material

· Old fluvial terraces

· On high-lying old erosion surfaces

· The most extensive areas of Oxisols are in sediments that have been reworked during several erosional and depositional cycles

· Materials which weather rapidly

· Parent material which consists of quartz, 1:1 type clays, iron and aluminum oxides

Spodosols:

Soils with subsoil accumulation of humus and sesquioxides

· Typically, Spodosols are formed in very coarse silty or coarser (i.e., increase in sand) textured material (e.g. sandy loam, loamy sand, sand)

· In the U. S. most Spodosols occur in late-Pleistocene or Holocene deposits (Ca leached before spodic horizon developed)

· Siliceous or leached carbonaceous parent materials favor the development of Spodosols

· Weathered material from rocks poor in Ca and Mg (e.g. sandstone, granite)

Ultisols:

Low base status soils

· Parent materials which contain few basic cations such as siliceous crystalline rocks (e.g. granite)

· Sedimentary material that is relatively poor in bases (e.g. highly weathered coastal plain sediment)

· Most of geologically old landscapes are covered by parent material rich in silica but poor in bases

· There are some Ultisols formed in parent material with higher base status and less weathered material (e.g. volcanic ash, basic ignenous or metamorphic rocks):

Basic parent material ® high precipitation ® rapid weathering ® rapid leaching of bases

Vertisols:

Shrinking and swelling dark clay soils

· Wide range of parent material including alluvial, colluvial and lacustrine deposits

· Marl and other calcareaous rocks, limestone, shales, igneous, metamorphic and volcanic rocks of basic nature

· Unconsolidated sediments which are dominantely basic in character and low in quartz

· The parent material although variable in origin, are rich in feldspars and ferro-magnesian minerals and yield clay residues on weathering

· Vertisols may develop in situ from the parent materials. The smectites in these soils could be derived from the original rock or form as a result of neogenesis or transformations from primary minerals.

· Characteristics: high clay content (predominance of 2:1 type expanding clay -> montmorillonite, smectite)

12.13.2) Summary properties of Entisols, Inceptisols, Vertisols, Andisols and Histosols

Entisols:

Characteristically have A/C or A/R profiles, exhibit only ephemeral soil development - largely confined to surface horizon. May have an Ap horizon.

Suborders:

- Aquents - exhibit wetness features
- Arents - distinctive plow layer
- Fluvents - formed in alluvial deposists
- Orthents - loamy or clayey textures
- Psamments - sandy textures

Inceptisols:

Characterized by ochric epipedon and incipient B horizon development (Cambic ~ Bw)

Suborders:

- Aquepts - exhibit wetness features
- Anthrepts - anthropic or plaggen epipedon
- Cryepts - cryic soil temp. regime
- Ustepts - ustic soil moist. regime
- Xerepts - xeric soil moist. regime
- Udepts - other Inceptisols (i.e., udic soil moist. regime)

Vertisols:

Mineral soils that (i) are over 50cm thick, (ii) have more than 30% clay in all horizons, and (iii) have cracks at least 1 cm wide to depth of 50 cm at some time in most years (unless irrigated). Conditions that give rise to Vertisols are: (i) parent materials that are high in, or that weather to form, large amounts of 2:1 expanding clay and (ii) occur in a climate with a pronounced wet and dry season - sufficient to promote cracking.

Suborders:

- Torrerts - see Aridic-type moisture regime
- Uderts - see Udic moisture regime
- Usterts - see Ustic moisture regime
- Xererts - see Xeric moisture regime
- Cryerts - see Cryic temperature regime

Histosols:

Organic soils, see definition of Histic epipedon for minimum limits on organic carbon, but note that most Histosols exceed depth requirements for histic epipedon.

Suborders:

- Folists -leaf mat accumulations above R horizon
- Fibrists - slight decomposition
- Hemists - intermediate decomposition
- Saprists - highly decoposed

Gelisols:

The central concept of Gelisols are soils with gelic materials underlain by permafrost. Diagnostic horizons may or may not be present. Permafrost influences pedogenesis by acting as a barrier to the downward movement of the soil solution.

Cryoturbation (frost mixing) is an important process in many Gelisols and results in irregular or broken horizons, involutions, organic matter accumulation on the permafrost table, oriented rock fragments, and silt caps on rock fragments. Cryoturbation occurs when two freezing fronts, one from the surface and the other from the permafrost, merge during freeze-back in the autumn.

Suborders:

- Histels - histic epipedon
- Turbels - evidence of cryoturbation
- Orthels - other Glelisols.

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