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LECTURE NOTES ON THE MAJOR SOILS OF THE WORLD

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World Soil Resources Reports **94**

LECTURE NOTES ON THE MAJOR SOILS OF THE WORLD

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Preface

After endorsement of the World Reference Base for Soil Resources (WRB) as a universal soil correlation tool by the International Union of Soil Sciences (IUSS), the Reference Base (RB) working group has endeavoured to promote, test and improve the system further .

The aim of this publication is to make the WRB available to young scientists at an affordable price. This text is published in conjunction with a CD-ROM that contains additional sample profiles, analytical data and virtual field excursions. The document and the CD-ROM are produced jointly by the Wageningen Agricultural University (Wageningen, The Netherlands), the International Institute for Aerospace Survey and Earth Sciences (ITC, Enschede, The Netherlands), the International Soil Reference and Information Centre (ISRIC, Wageningen, The Netherlands), the Faculty of Agricultural Sciences of the Katholieke Universiteit Leuven (Belgium) and FAO. This publication succeeds the *Lecture notes on the major soils of the world* by P.M. Driessen and R. Dudal, eds. (1991) which were based on the Legend of the FAO Soil Map of the World.

For convenience, all WRB Reference Soil Groups are assembled in ten 'sets', each characterized by 'dominant identifiers', i.e. soil forming factor(s) which most clearly condition soil formation. Each Reference Soil Group is discussed with due attention to diagnostics, regional distribution, association with other Reference Soil Groups, genesis, characteristics (morphological, hydrological, physical and chemical), land use and management.

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Berding, F.R.	Gleysols, Umbrisols, Arenosols, Regosols, Andosols, Gypsisols, Calcisols, Durisols, Podzols , Qualifyer categories and their ranking
Blume, H.P.	Gleysols
Brahy, V.	Alisols
Buurman, P.	Podzols
Deckers, J. A.	Vertisols, Luvisols, Albeluvisols
Delvaux, B.	Alisols
Driessen, P.M.	Introduction, Histosols, Arenosols, Leptosols, Regosols, Cambisols, Plinthosols, Ferralsols, Nitisols, Acrisols, Lixisols, Solonchaks, Solonetz, Gypsisols, Calcisols, Chernozems, Kastanozems, Phaeozems, Planosols, final editing of all chapters
Dudal, R.	Critical review of the entire text, with special attention for Luvisols
Langohr, R.	Albeluvisols
Mensvoort, M. van	Gleysols, Fluvisols
Nachtergaele, F. O.	Qualifyers, maps, critical review of the entire text
Spaargaren, O. C.	Anthrosols
Tarnocai, C.	Cryosols
Tebbens, L.	All chapter on Major Landforms
Veldkamp, T.	All chapters on Major Landforms.

Messrs J. P. Lesschen and N. Witte produced the CD-ROM.

These lecture notes will be progressively improved. Suggestions for amendments or additions are most welcome.

Rome, June, 2001

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Introduction

Soil is a 3-dimensional body with properties that reflect the impact of (1) *climate*, (2) *vegetation, fauna, Man* and (3) *topography* on the soil's (4) *parent material* over a variable (5) *time* span. The nature and relative importance of each of these five *'soil forming factors'* vary in time and in space. With few exceptions, soils are still in a process of change; they show in their *'soil profile'* signs of differentiation or alteration of the soil material incurred in a process of soil formation or *'pedogenesis'*.

Unlike plants and animals, which can be identified as separate entities, the world's soil cover is a continuum. Its components occur in temporal and/or spatial successions. In the early days of soil science, soil classification was based on the (surmised) genesis of the soils. Many 'traditional' soil names refer to the soil forming factor considered to be dominant in a particular pedogenetic history, for instance 'desert soils' (climate being the dominant factor), 'plaggen soils' (human interference), 'prairie soils' (vegetation), 'mountain soils' (topography), or 'volcanic ash soils' (parent material). Alternatively, soil names referred to a prominent single factor, for instance 'Brown Soils' (colour), 'alkali soils' (chemical characteristic), 'hydromorphic soils' (physical characteristic), 'sandy soils' (texture) or 'lithosols' (depth).

The many soil classification schemes developed over the years reflect different views held on concepts of soil formation and mirror differences of opinion about the criteria to be used for classification. In the 1950's, international communications intensified while the number of soil surveys increased sharply both in temperate regions and in the tropics. The experience gained in those years and the exchange of data between scientists rekindled interest in (the dynamics of) the world's soil cover. Classification systems were developed, which aimed at embracing the full spectrum of the soil continuum. In addition, emphasis shifted away from the genetic approach, which often contained an element of conjecture, to the use of soil *properties* as differentiating criteria. By and large, consensus evolved as to the major soil bodies which needed to be distinguished in broad level soil classification although differences in definitions and terminology remained.

The FAO-Unesco soil classification system

In 1974, the Food and Agriculture Organization of the United Nations (FAO) published its Soil Map of the World (SMW). Compilation of the SMW was a formidable task involving collection and correlation of soil information from all over the world. Initially, the Legend to the SMW consisted of 26 ('first level') "Major Soil Groupings" comprising a total of 106 ('second level') 'Soil Units'.

In 1990, a 'Revised Legend' was published and a third hierarchical level of 'Soil Subunits' was introduced to support soil inventory at larger scales. Soil Subunits were not defined as such but guidelines for their identification and naming were given. De facto this converted the SMW map legend, with a finite number of entries, into an open-ended, globally applicable 'FAO-Unesco Soil Classification System'.

The World Reference Base for soil resources

In 1998, the International Union of Soil Sciences (IUSS) officially adopted the *World Reference Base for Soil Resources* (WRB) as the Union's system for soil *correlation*. The structure, concepts and definitions of the WRB are strongly influenced by (the philosophy behind and experience gained with) the FAO-Unesco Soil Classification System. At the time of its inception, the WRB proposed 30 '*Soil Reference Groups*' accommodating more than 200 ('second level') *Soil Units*.

In the present text, the 30 Reference Soil Groups are aggregated in 10 'sets' composed as follows:

1. First, a separation is made between *organic soils* and *mineral soils*; all organic soils are grouped in Set #1.
2. The remaining (mineral) Major Soil Groups are each allocated to one of nine sets on the basis of *'dominant identifiers'*, i.e. those soil forming factor(s) which most clearly conditioned soil formation.

Table 1 summarises the 10 sets, their dominant identifiers and the Reference Soil Groups within each set.

SET #1 holds all soils with more than a defined quantity of *'organic soil materials'*. These organic soils are brought together in only one Reference Soil Group: the HISTOSOLS.

SET #2 contains all *man-made soils*. These soils vary widely in properties and appearance and can occur in any environment but have in common that their properties are strongly affected by human intervention. They are aggregated to only one Reference Soil Group: the ANTHROSOLS.

SET #3 includes mineral soils whose formation is conditioned by the particular properties of their *parent material*. The set includes three Reference Soil Groups:

1. the ANDOSOLS of volcanic regions,
2. the sandy ARENOSOLS of desert areas, beach ridges, inland dunes, areas with highly weathered sandstone, etc., and
3. the swelling and shrinking heavy clayey VERTISOLS of backswamps, river basins, lake bottoms, and other areas with a high content of expanding 2:1 lattice clays.

SET #4 accommodates mineral soils whose formation was markedly influenced by their *topographic/physiographic setting*. This set holds soils in low terrain positions associated with recurrent floods and/or prolonged wetness, but also soils in elevated or accidented terrain where soil formation is hindered by low temperatures or erosion.
The set holds four Reference Soil Groups:
In low terrain positions:

1. Young *alluvial* FLUVISOLS, which show stratification or other evidence of recent sedimentation, and
2. Non-stratified GLEYSOLS in *waterlogged areas* that do not receive regular additions of sediment.

In elevated and/or eroding areas:

3. *Shallow* LEPTOSOLS over hard rock or highly calcareous material, and
4. Deeper REGOSOLS, which occur in *unconsolidated materials* and which have only *surficial profile development*, e.g. because of low soil temperatures, prolonged dryness or erosion.

SET #5 holds soils that are only moderately developed on account of their *limited pedogenetic age* or because of *rejuvenation* of the soil material. Moderately developed soils occur in all environments, from sea level to the highlands, from the equator to the boreal regions, and under all kinds of vegetation. They have not more in common than *'signs of beginning soil formation*' so that there is considerable diversity among the soils in this set. Yet, they all belong to only one Reference Soil Group: the CAMBISOLS.

SET #6 accommodates the 'typical' red and yellow soils of *wet tropical and subtropical regions*. High soil temperatures and (at times) ample moisture promote rock weathering and rapid decay of soil organic matter. The Reference Soil Groups in this set have in common that a long history of dissolution and transport of weathering products has produced deep and genetically mature soils:

1. PLINTHOSOLS on old weathering surfaces; these soils are marked by the presence of a mixture of clay and quartz (*'plinthite'*) that hardens irreversibly upon exposure to the open air,
2. deeply weathered FERRALSOLS that have a very *low cation exchange capacity* and are virtually devoid of weatherable minerals,
3. ALISOLS with *high cation exchange capacity* and *much exchangeable aluminium*,
4. deep NITISOLS in relatively rich parent material and marked by *shiny, nutty structure elements*,
5. strongly leached, red and yellow ACRISOLS on acid parent rock, with a *clay accumulation horizon*, *low cation exchange capacity* and *low base saturation*, and
6. LIXISOLS with a *low cation exchange capacity* but *high base saturation percentage*.

SET #7 accommodates Reference Soil Groups in *arid and semi-arid regions*. Redistribution of calcium carbonate and gypsum is an important mechanism of horizon differentiation in soils in the dry zone. Soluble salts may accumulate at some depth or, in areas with shallow groundwater, near the soil surface. The Reference Soil Groups assembled in set #7 are:

1. SOLONCHAKS with a high content of *soluble salts*,
2. SOLONETZ with a high percentage of *adsorbed sodium ions*,
3. GYPSISOLS with a horizon of *secondary gypsum enrichment*,
4. DURISOLS with a layer or nodules of soil material that is *cemented by silica*, and
5. CALCISOLS with *secondary carbonate enrichment.*

SET #8 holds soils that occur in the *steppe zone* between the dry climates and the humid Temperate Zone. This transition zone has a climax vegetation of ephemeral grasses and dry forest; its location corresponds roughly with the transition from a dominance of accumulation processes in soil formation to a dominance of leaching processes. Set #8 includes three Reference Soil Groups:

1. CHERNOZEMS with *deep, very dark surface soils* and *carbonate enrichment* in the subsoil,
2. KASTANOZEMS with *less deep, brownish surface soils and carbonate and/or gypsum accumulation* at some depth (these soils occur in the driest parts of the steppe zone), *and*
3. PHAEOZEMS, the dusky red soils of prairie regions with *high base saturation* but *no visible signs of secondary carbonate accumulation.*

SET #9 holds the brownish and greyish soils of *humid temperate regions*. The soils in this set show evidence of redistribution of clay and/or organic matter. The cool climate and short genetic history of most soils in this zone explain why some soils are still relatively rich in bases despite a dominance of eluviation over enrichment processes. Eluviation and illuviation of metal-humus complexes produce the greyish (bleaching) and brown to black (coating) colours of soils of this set. Set #9 contains five Reference Soil Groups:

1. acid PODZOLS with a *bleached eluviation horizon* over an *accumulation horizon* of organic matter with aluminium and/or iron,
2. PLANOSOLS with a bleached topsoil over *dense, slowly permeable subsoil*,
3. base-poor ALBELUVISOLS with a *bleached eluviation horizon tonguing* into a *clay-enriched subsurface horizon*,
4. base-rich LUVISOLS with a distinct *clay accumulation horizon*, and
5. UMBRISOLS with a thick, *dark, acid surface horizon* that is rich in organic matter.

SET #10 holds the soils of *permafrost regions*. These soils show signs of *'cryoturbation'* (i.e. disturbance by freeze-thaw sequences and ice segregation) such as irregular or broken soil horizons and organic matter in the subsurface soil, often concentrated along the top of the permafrost table. Cryoturbation also results in oriented stones in the soil and sorted and non-sorted patterned ground features at the surface. All 'permafrost soils' are assembled in one Reference Soil Group: the CRYOSOLS.

Note that the Reference Soil Groups in sets #6 through #10 represent soils, which occur predominantly in specific climate zones. Such soils are known as '*zonal soils*'. Be aware, however, that *not all* soils in sets #6 through #10 are zonal soils, nor are soils in other sets always non-zonal. Podzols, for instance, are most common in (sub)humid temperate climates (set #9) but they are also found in the humid tropics; Planosols may equally occur in subtropical and steppe climates and Ferralsols may occur as remnants outside the humid tropics. Soils whose characteristics result from the strong *local* dominance of a soil forming factor other than 'climate' are not 'zonal soils'. They are *'intrazonal soils'*. In other words there are zonal and intrazonal Podzols, zonal and intrazonal Gleysols, zonal and intrazonal Histosols, and many more. Some soils are too young to reflect the influence of site-specific conditions in their profile characteristics; these are *'azonal soils*'. Young alluvial soils (Fluvisols) and soils in recent hillwash (e.g. Cambisols) are examples of azonal soils. The zonality concept helps to understand (some of) the diversity of the global soil cover but is a poor basis for soil classification. The sets of Reference Soil Groups presented in this text may therefore not be seen as high level classification units but merely as an illustration how basic principles of soil formation manifest themselves in prominent global soil patterns.

TABLE 1
All Reference Soil Groups of the WRB assembled in 10 sets

SET #1	Organic soils	HISTOSOLS
SET #2	Mineral soils whose formation was conditioned by *human influences* (not confined to any particular region)	ANTHROSOLS
SET #3	Mineral soils whose formation was conditioned by their *parent material* - Soils developed in *volcanic material* - Soils developed in *residual and shifting sands* - Soils developed in *expanding clays*	 ANDOSOLS ARENOSOLS VERTISOLS
SET #4	Mineral soils whose formation was conditioned by the *topography/physiography* of the terrain - Soils in *lowlands (wetlands) with level topography* - Soils in *elevated regions with non-level topography*	 FLUVISOLS GLEYSOLS LEPTOSOLS REGOSOLS
SET #5	Mineral soils whose formation is conditioned by their *limited age* (not confined to any particular region)	CAMBISOLS
SET #6	Mineral soils whose formation was conditioned by *climate: (sub-)humid tropics*	PLINTHOSOLS FERRALSOLS NITISOLS ACRISOLS ALISOLS LIXISOLS
SET #7	Mineral soils whose formation was conditioned by *climate: arid and semi-arid regions*	SOLONCHAKS SOLONETZ GYPSISOLS DURISOLS CALCISOLS
SET #8	Mineral soils whose formation was conditioned by *climate: steppes and steppic regions*	KASTANOZEMS CHERNOZEMS PHAEOZEMS
SET #9	Mineral soils whose formation was conditioned by *climate: (sub-)humid temperate regions*	PODZOLS PLANOSOLS ALBELUVISOLS LUVISOLS UMBRISOLS
SET #10	Mineral soils whose formation was conditioned by *climate: permafrost regions*	CRYOSOLS

Diagnostic horizons, properties and materials

The taxonomic units of the WRB are defined in terms of measurable and observable '*diagnostic horizons*', the basic identifiers in soil classification. Diagnostic horizons are defined by (combinations of) characteristic *'soil properties'* and/or *'soil materials'*. The diagnostic horizons, properties and materials used by the WRB to differentiate between Reference Soil Groups are described hereafter in Tables 2, 3 and 4; their full definitions can be found in Annex 2 to this text.

Note that a distinction must be made between the soil horizon designations used in soil profile descriptions and diagnostic horizons as used in soil classification. The former belong to a nomenclature in which master horizon codes (H, O, A, E, B, C and R) are assigned to the various soil horizons in a soil profile when it is described and interpreted in the field. The choice of horizon code is by personal judgement of the soil surveyor. Diagnostic horizons, on the other hand, are rigidly defined and their presence or absence can be ascertained on the basis of unambiguous field and/or laboratory measurements. Some of the diagnostic horizons in the WRB soil correlation system are special forms of A- or B-horizons, e.g. a *'mollic'* A-horizon, or a *'ferralic'* B-horizon. Other diagnostic horizons are not necessarily A- or B-horizons, e.g. a *'calcic'* or a *'gypsic'* horizon.

TABLE 2
Descriptive overview of diagnostic horizons (see Annex 2 for full definitions)

Surface horizons and subsurface horizons at shallow depth	
anthropogenic horizons	surface and subsurface horizons resulting from long-continued *'anthropedogenic processes'*, notably deep working, intensive fertilisation, addition of earthy materials, irrigation or wet cultivation.
chernic horizon	deep, well-structured, blackish surface horizon with a *high base saturation*, *high organic matter content, strong biological activity* and *well-developed, usually granular, structure*. Its carbon content is intermediate between a *mollic* horizon and a *histic* horizon.
folic horizon	surface horizon, or subsurface horizon at shallow depth, consisting of *well-aerated organic soil material*.
fulvic horizon	*thick, black surface horizon* having a *low bulk density* and *high organic carbon content* conditioned by short-range-order minerals (usually *allophane*) and/or *organo-aluminium complexes*.
histic horizon	*(peaty) surface horizon,* or subsurface horizon occurring at shallow depth, consisting of *organic soil material*.
melanic horizon	thick, black surface horizon conditioned by short-range-order minerals (usually *allophane*) and/or *organo-aluminium complexes*. Similar to the fulvic horizon except for a *'melanic index[1]'* of 1.70 or less throughout.
mollic horizon	well-structured, *dark* surface horizon with *high base saturation* and *moderate to high organic carbon content*.
takyric horizon	finely textured surface horizon consisting of a dense surface crust and a platy lower part; formed under arid conditions in periodically flooded soils.
umbric horizon	well-structured, *dark* surface horizon with *low base saturation* and *moderate to high organic matter content.*
ochric horizon	surface horizon *without stratification*, which is either *light coloured*, or *thin*, or has a *low organic carbon content*, or is *massive and (very) hard when dry*.
vitric horizon	surface or subsurface horizon *rich in volcanic glass* and other primary minerals associated with volcanic ejecta.
yermic horizon	surface horizon of *rock fragments ('desert pavement')* usually, but not always, embedded *in a vesicular crust* and covered by a thin aeolian sand or loess layer.
Subsurface horizons	
albic horizon	bleached eluviation horizon with the colour of uncoated soil material, usually overlying an illuviation horizon.
andic horizon	horizon evolved during *weathering of mainly pyroclastic deposits*; mineral assemblage dominated by short-range-order minerals such as allophane.
argic horizon	subsurface horizon having distinctly more clay than the overlying horizon as a result of *illuvial accumulation of clay and/or pedogenetic formation of clay in the subsoil* and/or destruction or selective erosion of clay in the surface soil.
cambic horizon	genetically young subsurface horizon showing evidence of alteration relative to underlying horizons: *modified colour, removal of carbonates or presence of soil structure*.
cryic horizon	*perennially frozen* horizon in *mineral* or *organic soil materials.*
calcic horizon	horizon with distinct *calcium carbonate enrichment*.
duric horizon	subsurface horizon with *weakly cemented to indurated nodules cemented by silica* (SiO_2) known as *'durinodes'*.
ferralic horizon	*strongly weathered* horizon in which the clay fraction is dominated by *low activity clays* and the sand fraction by *resistant materials* such as iron-, aluminium-, manganese- and titanium oxides.

[1] The melanic index (MI) is the ratio of absorbance of NaOH-extractable humus at 450 and 520 nm. See: Honna T., S. Yamamoto and K. Matsui. 1988. A simple procedure to determine the melanic index that is useful for differentiating Melanic from Fulvic Andisols. Pedologist, Vol.32 No 1, 69-75.

TABLE 2 (continued)
Descriptive overview of diagnostic horizons (see Annex 2 for full definitions)

ferric horizon	subsurface horizon in which *segregation of iron* has taken place to the extent that large mottles or concretions have formed in a matrix that is largely depleted of iron.
fragic horizon	*dense, non-cemented* subsurface horizon that can *only* be penetrated by roots and water along natural cracks and streaks.
gypsic horizon	horizon with distinct *calcium sulphate enrichment*.
natric horizon	subsurface horizon with *more clay than any overlying horizon(s)* and *high exchangeable sodium percentage*; usually dense, with *columnar or prismatic structure*.
nitic horizon	clay-rich subsurface horizon with a moderate to strong *polyhedric or nutty structure with shiny ped faces*.
petrocalcic horizon	continuous, cemented or indurated *calcic* horizon.
petroduric horizon	continuous subsurface horizon cemented mainly by *secondary silica* (SiO_2), also known as a *'duripan'*.
petrogypsic horizon	*cemented* horizon containing *secondary accumulations of gypsum* ($CaSO_4.2H_2O$).
petroplinthic horizon	continuous layer *indurated by iron compounds* and without more than traces of organic matter.
plinthic horizon	subsurface horizon consisting of an *iron-rich, humus-poor mixture of kaolinitic clay with quartz* and other constituents, and which *changes irreversibly to a hardpan or to irregular aggregates* on exposure to repeated wetting and drying with free access of oxygen.
salic horizon	surface or shallow subsurface horizon containing 1 percent of *readily soluble salts* or more.
spodic horizon	dark coloured subsurface horizon with *illuvial amorphous substances* composed of *organic matter and aluminium, with or without iron*.
sulfuric horizon	*extremely acid* subsurface horizon in which *sulphuric acid has formed through oxidation of sulphides*.
vertic horizon	subsurface horizon *rich in expanding clays* and having *polished and grooved ped surfaces ('slickensides'*), or *wedge-shaped* or *parallelepiped structural aggregates* formed upon repeated swelling and shrinking.

TABLE 3
Descriptive summary of diagnostic properties (see Annex 2 for full definitions)

abrupt textural change	very *sharp increase in clay content* within a limited vertical distance.
albeluvic tonguing	*iron-depleted material penetrating* into an *argic* horizon along ped surfaces.
alic properties	*very acid* soil material with a *high* level of *exchangeable aluminium*.
aridic properties	refer to soil material *low in organic matter*, with evidence of *aeolian activity*, *light in colour* and (virtually) *base-saturated.*
continuous hard rock	material which is sufficiently *coherent and hard* when moist to make digging with a spade impracticable.
ferralic properties	indicate that the (mineral) soil material has a *'low' cation exchange capacity* or would have qualified for a *ferralic horizon if it had been less coarsely textured*.
geric properties	mark soil material of very *low effective cation exchange capacity* or even acting as anion exchanger.
gleyic properties	visible evidence of prolonged *waterlogging by shallow groundwater.*
permafrost	indicates that the *soil temperature is perennially at or below* $0\,^{o}C$ for at least two consecutive years.
secondary carbonates	significant quantities of *translocated lime*, soft enough to be readily cut with a finger nail, precipitated from the soil solution rather than being inherited from the soil parent material.
stagnic properties	visible evidence of prolonged *waterlogging by a perched water table*.
strongly humic properties	indicative of a *high content of organic carbon* in the upper metre of the soil.

TABLE 4
Descriptive summary of diagnostic materials (see Annex 2 for full definitions)

anthropogenic soil material	unconsolidated mineral or organic material *produced largely by human activities* and not significantly altered by pedogenetic processes.
calcaric soil material	soil material, which contains more than 2 percent calcium carbonate equivalent and shows *strong effervescence with 10 percent HCl* in most of the fine earth.
fluvic soil material	*fluviatile, marine and lacustrine sediments*, which show *stratification* in at least 25 percent of the soil volume over a specified depth and/or have an *organic carbon content decreasing irregularly with depth*.
gypsiric soil material	mineral soil material, which contains *5 percent or more gypsum (by volume)*.
organic soil material	*organic debris*, which accumulates *at the surface* and in which the mineral component does not significantly influence soil properties.
sulfidic soil material	*waterlogged deposit containing sulphur*, mostly sulphides, and *not more than moderate amounts of calcium carbonate*.
tephric soil material	unconsolidated, non or only slightly weathered *products of volcanic eruptions*, with or without admixtures of material from other sources.

Note that the generalised descriptions of diagnostic horizons, properties and soil materials given in Tables 2, 3 and 4 are solely meant as a first introduction to WRB terminology. The exact concepts and full definitions presented in Annex 2 must be used for identifying diagnostic horizons, properties and materials in practical taxon identification.

The World Reference Base for Soil Resources

The WRB as a soil correlation system
Rules for identifying Soil Units
Ranking qualifiers in Soil Unit names
Polygenetic and buried soils

The World Reference Base for Soil Resources

THE WRB AS A SOIL CORRELATION SYSTEM

The objectives of the World Reference Base are twofold. On the one hand the WRB is intended to be a reference system for users interested in a broad division of soils, at the highest level of generalisation and explained in non-technical terms. On the other hand, the WRB must facilitate soil correlation across a wide range of national soil classification systems.

To best reconcile such conflicting requirements, it was decided to design the WRB as a flexible system, with maximum use of '*morphometric*' (from Gr. *morphos* 'shape' and L. *metrum* 'size') soil profile information, but with rigidly standardised definitions. Using standardised diagnostic criteria and qualifiers facilitates soil correlation and technology transfer between countries and regions, which helps to better understand (relations between) soil resources and facilitates regional application of soil information, e.g. in land use planning.

Reference Soil Groups are distinguished by the presence (or absence) of specific *diagnostic horizons, properties* and/or *materials*. A limited number of '*qualifiers*', with unique definitions, describe individual *Soil Units* within Reference Soil Groups.

Annex 1 to this text presents the full key for identifying WRB Reference Soil Groups; Annex 2 defines the diagnostic horizons, properties and materials used to define the various Reference Soil Groups.

Note that the number of Reference Soil Groups in the WRB is fixed (30) but the number of Soil Units is not. Soil Units are distinguished on the basis of distinct 'Rules for identifying Soil Units' (see hereafter); qualifiers used to identify Soil Units are presented in Annex 3.

RULES FOR IDENTIFYING SOIL UNITS

1. Soil units are defined, and named, on the basis of WRB-approved 'qualifiers'. See Annex 3.

2. Qualifier names can be used in combination with indicators of depth, thickness or intensity. For instance, an Epi-Dystric Luvisol is a soil unit name in which 'Epi-' signifies shallow depth whereas 'Dystric' is a qualifier indicative of a low base status. If more than two qualifiers are needed, these are listed behind the Reference Soil Group name (between brackets), e.g. Acri-Geric Ferralsol (Abruptic and Xanthic).

3. Names of soil units must not overlap or conflict with names of other soil units or with Reference Soil Group definitions. For example, a "Dystri-Petric Calcisol" is unacceptable because it contains a contradiction ('Dystri-' is incompatible with 'Calcisol') and a "Eutri-Petric Calcisol" is rejected because the qualifier "Eutri-" overlaps with information inherent to the Reference Soil Group name "Calcisol".

4. New units can only be established if documented by a soil profile description and supporting laboratory analyses.

Qualifiers are defined by unique sets of diagnostic criteria. Most diagnostic criteria in qualifier definitions are derived from already established Reference Soil Group criteria such as diagnostic horizons, properties and materials. Weak or incomplete occurrences of features are generally not considered to be differentiating. Attributes referring to climate, parent material, vegetation or to physiographic features such as slope, geomorphology or erosion, are *not* used to differentiate between soil units. Neither are soil-water related attributes such as depth of water table or drainage, substratum specifications, nor specifications of thickness and/or morphology of the solum or individual horizons.

Ranking qualifiers in Soil Unit names

It is widely felt that indiscriminate use of qualifiers would create confusion but the precise ranking of qualifiers in Soil Unit names is currently still under discussion. Annex 4 presents *tentative* ranking orders suggested for common qualifiers within each Reference Soil Group.

An example:

Within the Reference Soil Group of the Vertisols, the following qualifiers are considered to be 'common' (See Annex 4):

Intergrades:

1.	Thionic	intergrade to acid sulphate Gleysols, Fluvisols and Cambisols
2.	Salic	intergrade to the Reference Soil Group of the Solonchaks
3.	Natric	intergrade to the Reference Soil Group of the Solonetz
4.	Gypsic	intergrade to the Reference Soil Group of the Gypsisols
5.	Duric	intergrade to the Reference Soil Group of the Durisols
6.	Calcic	intergrade to the Reference Soil Group of the Calcisols
7.	Alic	intergrade to the Reference Soil Group of the Alisols

Extragrades:

8.	Gypsiric	containing gypsum
9.	Grumic	having a mulched surface horizon
10.	Mazic	having a very hard surface horizon; workability problems
11.	Mesotrophic	having less than 75 percent base saturation
12.	Hyposodic	having an ESP of 6 to 15
13.	Eutric	having 50 percent or more base saturation
14.	Pellic	dark coloured, often poorly drained
15.	Chromic	reddish coloured
16.	Haplic	no specific characteristics

A reddish coloured Soil Unit within the Reference Soil Group of the *Vertisols,* having a *calcic horizon,* would be classified as a Calci-Chromic Vertisol because qualifiers 6 and 15 apply. If information on depth and intensity of the calcic horizon is available, e.g. occurring near the surface, one would classify the soil as an EpiCalci-Chromic Vertisol (indicating that the calcic horizon occurs within 50 cm from the surface).

If more than two qualifiers are needed, these are added behind the Reference Soil Group name. If, for instance, the Vertisol discussed would also feature a very hard surface horizon (qualifier 10), the soil would be named a Calci-Chromic Vertisol (Mazic).

Polygenetic and buried soils

Soils have vertical and horizontal dimensions that evolved over time. The vertical dimension is for practical purposes limited to a "control section" with a depth of 100 cm or, exceptionally, 200 cm below the surface. The qualifier *bathic* can be used to refer to horizons, properties or characteristics that occur below the control section.

Most soil profiles can be named without difficulty but some, more complex situations require additional classification guidelines. The WRB prefers to name soils as they occur, i.e. with present-day characteristics and functional behaviour, rather than emphasising their (supposed) genetic history. It is realised however that few soils have completely evolved in situ and that it may be useful in certain cases to indicate this. Some soils show signs of *polygenetic development* i.e. a different soil has evolved prior to the present one (often under different environmental conditions) and both soils can be classified. A qualifier *thapto-* indicates the presence of a *buried soil* or a *buried horizon*. This would be the case if a soil has a surface mantel of new material that is 50 cm thick or more. The surface mantel is named in the normal way (e.g. as a Regosol, Andosol or Arenosol) and the buried soil would be classified with a prefix qualifier '*thapto-*'. If the surface mantle is less than 50 cm thick, it is ignored in the soil name but the soil may be marked on the soil map by a phase indicator.

Note that it is not recommended to systematically include the qualifier *thapto-* if this adds no information that has practical implications for the user.

Reference Soil Groups

Set #1

ORGANIC SOILS

Histosols

HISTOSOLS (HS)

The Reference Soil Group of the Histosols comprises soils formed in 'organic soil material[@]'. These vary from soils developed in (predominantly) moss peat in boreal, arctic and subarctic regions, via moss peat, reeds/sedge peat and forest peat in temperate regions to mangrove peat and swamp forest peat in the humid tropics. Histosols are found at all altitudes but the vast majority occurs in lowlands. Common international names are 'peat soils', 'muck soils', 'bog soils' and 'organic soils'.

Definition of Histosols[#]

Soils,

1. having *a histic*[@] or *folic*[@] horizon*,*
   either 10 cm or more thick from the soil surface to a *lithic*[*] or *paralithic*[*] contact,
   or 40 cm or more thick and starting within 30 cm from the soil surface; and
2. having no *andic*[@] or *vitric*[@] horizon starting within 30 cm from the soil surface.

Common soil units:
Glacic[*], Thionic[*], Cryic[*], Gelic[*], Salic[*], Folic[*], Fibric[*], Sapric[*], Ombric[*], Rheic[*], Alcalic[*], Toxic[*], Dystric[*], Eutric[*], Haplic[*].

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
[*] Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Histosols

Connotation: peat and muck soils; from Gr. *histos*, tissue.

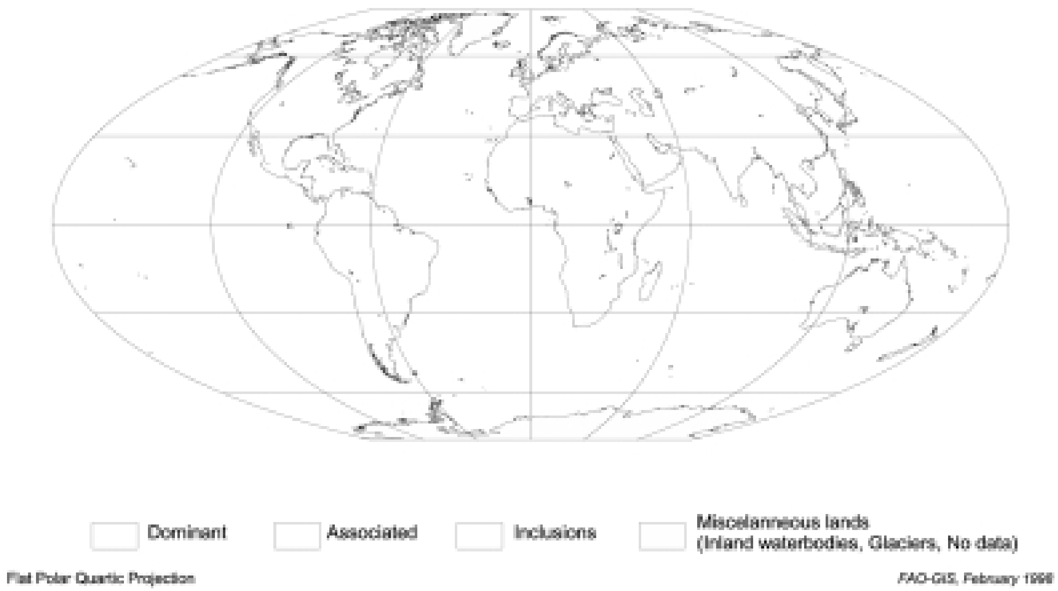
Parent material: incompletely decomposed plant remains, with or without admixtures of sand, silt or clay.

Environment: Histosols occur extensively in boreal, arctic and subarctic regions. Elsewhere, they are confined to poorly drained basins, depressions, swamps and marshlands with shallow groundwater, and highland areas with a high precipitation/evapotranspiration ratio.

Profile development: Transformation of plant remains through biochemical disintegration and formation of humic substances creates a surface layer of mould. Translocated organic material may accumulate in deeper tiers but is more often leached from the soil.

Use: Sustainable use of peat lands is limited to extensive forms of forestry or grazing. If carefully managed, Histosols can be very productive under capital-intensive forms of arable cropping/horticulture, at the cost of sharply increased mineralization losses. Deep peat formations and peat in northern regions are best left untouched. In places, peat bogs are mined, e.g. for production of growth substrate for horticulture, or to fuel power stations.

Figure 1
Histosols world-wide



Regional distribution of Histosols

The total extent of Histosols in the world is estimated at some 325 - 375 million ha, of which the majority are located in the boreal, subarctic and low arctic regions of the Northern Hemisphere. Most of the remaining Histosols occur in temperate lowlands and cool mountain areas; only one-tenth of all Histosols are found in the tropics. Extensive peat areas occur in the USA and Canada, Western Europe and northern Scandinavia, and in northern regions east of the Ural mountain range. Some 20 million hectares of tropical forest peat border the Sunda shelf in Southeast Asia. Smaller areas of tropical Histosols are found in river deltas, e.g. in the Orinoco delta and the delta of the Mekong River, and in depression areas at some altitude. Figure 1 presents a sketch map of the main occurrences of Histosols world-wide.

Associations with other Reference Soil Groups

Organic soil materials in northern regions could accumulate there because decay of organic debris is retarded by frost in the cold season and by prolonged water-saturation of the thawed surface soil during summer. Permafrost-affected Histosols are associated with *Cryosols* and with soils that have gleyic or stagnic properties, e.g. *Gleysols* in Alaska and in the northern part of the former USSR. Where the (sub)arctic region grades into the cool Temperate Zone, associations with *Podzols* can be expected.

Histosols that formed in organic soil material under the permanent influence of groundwater (‘*low moor peat*’) occupy the lower parts of fluvial, lacustrine and marine landscapes, mainly in temperate regions. Other soils in the same environment are *Fluvisols*, *Gleysols* and, in coastal regions, *Solonchaks* (e.g. adjacent to coastal mangrove peat). Histosols in lacustrine landforms are commonly associated with *Vertisols*.

Rain-dependent Histosols are found in environments with sufficiently high and evenly spread rainfall, e.g. in raised 'dome' peat formations ('*high moor peat*') in lowland areas and in upland areas with blanket peat, where paucity of nutrient elements, acidity and near-permanent wetness retard decay of organic debris. Lateral linkages exist with a variety of Reference Soil Groups, including *Andosols*, *Podzols*, *Fluvisols*, *Gleysols*, *Cambisols* and *Regosols*.

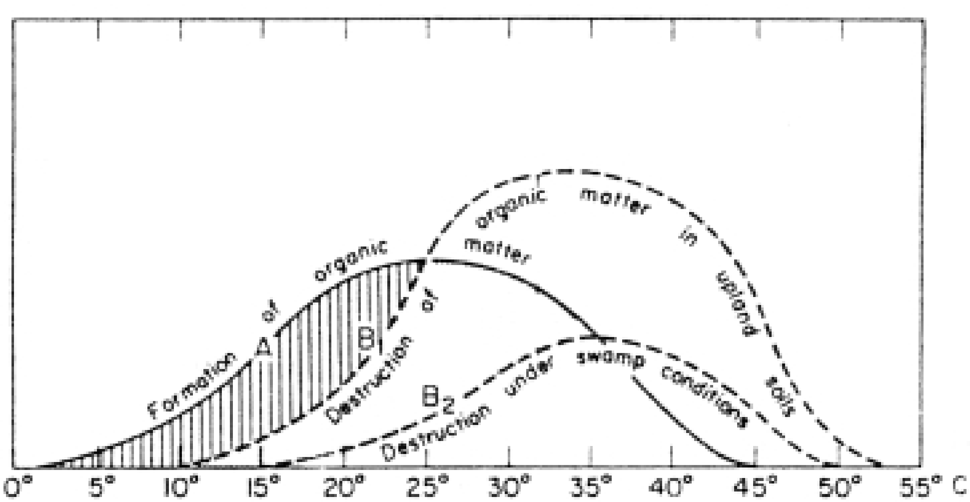
Genesis of Histosols

Histosols are unlike all other soils in that they are formed in '*organic soil material*' with physical, chemical and mechanical properties that differ strongly from those of mineral soil materials. 'Organic soil material' is soil material that contains more than 20 percent organic matter by weight, roughly equivalent to 30 – 35 percent by volume. Organic soil material accumulates in conditions where plant matter is produced by an adapted ('climax') vegetation, and where decomposition of plant debris is slowed by:

- low temperatures,
- persistent water saturation of the soil body,
- extreme acidity or paucity of nutrient elements ('*oligotrophy*'), and/or
- high levels of electrolytes or organic toxins.

Figure 2 indicates that a surplus of organic soil material can build up in cold and temperate regions, and under swamp conditions even in the tropics. Organic soil materials that formed in different environments are generally of different botanical composition; degrees of decomposition and contents of mineral admixtures are equally varied.

Figure 2
Comparative rates of production (A) and decomposition (B1 in aerated soil; B2 under water) of organic matter as influenced by the temperature and aeration status of the soil body. (Mohr, Van Baren & Van Schuylenborg, 1972)



Note: In view of the limited agricultural significance of the (extensive!) northern Histosols, and because Histosols in temperate and tropical climates are under much stronger attack, the following discussion will focus on Histosol development and Histosol deterioration in temperate and tropical climates.

The majority of all peat bogs in the Temperate Zone and in the tropics are found in lowland areas, e.g. in coastal plains and deltas and in fluvial and lacustrine inland areas. Local depressions/pools in such wetlands are gradually filled in with reeds and sedges and with the remains of aquatic plants that accumulate in the deeper parts. The margins of a depression area are the first to become 'dry'. This prompts the vegetation, differentiated in floral belts adapted to different degrees of wetness, to shift toward the center of the depression. Eventually, the entire depression is filled with '*topogenous peat*' (i.e. '*low moor peat*', formed under the influence of groundwater). The transition from the mineral substrata to the overlying peat body may be gradual but a thin transitional layer of black, smeary, completely decomposed organic sediment ('*gyttja*') is not uncommon (see Figure 3).

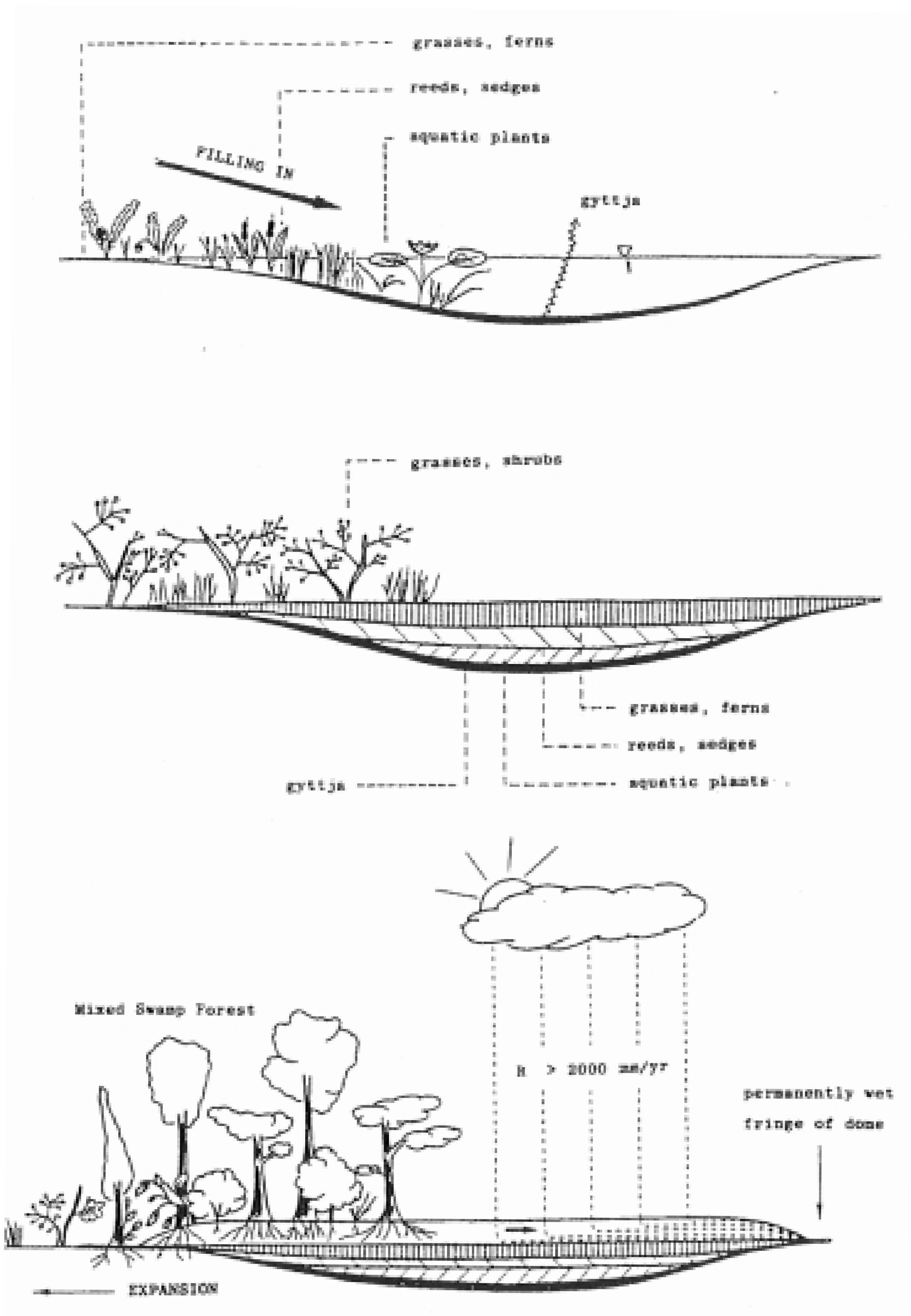
Topogenous peat is shallow by nature. Only where its accumulation coincides with gradual tectonic lowering of the land surface can it reach a great depth. Topogenous peat deposits in the Drama Plain, Greece, for instance, are in places deeper than 300 meters.

In upland areas where temperatures are 'low' and rainfall/fog is evenly spread over the year, rain-dependent '*ombrogenous peat*' (or '*high moor peat*') forms where microbial activity is depressed by severe acidity, oligotrophy and/or organic toxins. The 'blanket peat' in Scotland and Wales is an example of (shallow) ombrogenous peat that lies directly on top of hard bedrock.

Ombrogenous peat formations in lowland areas normally overlie topogenous peat. After a depression is completely filled with topogenous peat, accumulation of organic soil material *may* continue. This happens where rainfall is high and evenly spread over the year, and microbial activity is suppressed by low temperature, wetness, acidity/oligotrophy and/or salt or organic toxins. The then formed peat mass rises over the mean water level and becomes increasingly ombrogenous in character as it is ever less enriched with mineral material (clay, nutrients) carried on with floods. As long as a peat body is still shallow, the vegetation can draw nutrients from the underlying mineral base. Once the peat has grown to a depth that puts the subsoil out of the reach of living roots, uptake of nutrient elements from outside stops while losses of nutrients (e.g. through leaching) continue; the vegetation must survive on a gradually decreasing quantity of cycling nutrients. The (climax) vegetation adapts to this gradual change by becoming poorer in quality and species composition. An initially heavy *mixed swamp forest* degrades slowly into light *monotonous forest* with only few tree species, and ultimately into *stunted forest* which produces insufficient organic material for further vertical growth of the bog. The net rate of vertical peat accumulation seems to decrease over time according to a roughly exponential pattern. Carbon dating of deep (8 to 12 m) dome peat formations under swamp forest in Sarawak and Indonesia suggest an initial accumulation rate of 0.25 to 0.45 cm/year that decreased in the course of 3 to 5 millennia to 0.05 cm/year and less (Anderson, 1964).

As the peat mass rises over its surroundings, the continual precipitation surplus (a precondition for the formation of ombrogenous peat) drains away to the fringes of the bog where it creates a wet peripheral zone. Topogenous peat can grow there and become covered with ombrogenous peat later on. Peat bodies from several nuclei (depressions) in a plain will eventually merge into one coherent peat body. The limit to vertical growth, in combination with continuing lateral expansion, explains the characteristic dome shape of ombrogenous 'raised bogs'.

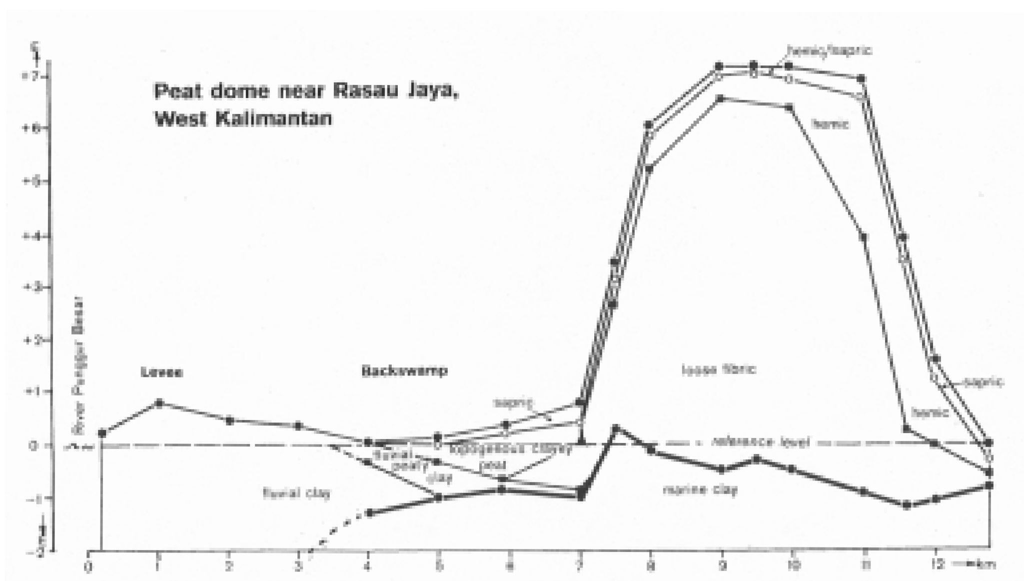
Figure 3
A depression is gradually filled in with topogenous peat, which is then overgrown by a laterally expanding ombrogenous peat mass. Note the changing composition of the vegetation



- *In northern regions*, peats are predominantly ombrogenous. Many occur in a 30-50 cm thawed (active) layer on top of permafrost subsoil.
- *In temperate regions*, topogenous '*low moor peat*' is mainly woody forest peat and peat derived from grassy marsh vegetation. The '*high moor peat*' of ombrogenous raised bogs is mostly moss (*Sphagnum*) peat. '*Blanket peat*' in upland areas is rain-dependent peat formed under heather and other low shrubs.
- *In the tropics*, lowland peat is almost exclusively ombrogenous and made up of woody rain forest debris. Topogenous peat in the tropics and subtropics is confined to comparatively small occurrences in coastal plains and lagoon areas and to filled-in lakes at high elevation. This peat is less woody than ombrogenous forest peat (e.g. *Papyrus* swamps, sawgrass peat, etc.) but richer in mineral constituents ('*ash*').

The degree of decomposition of organic soil material has direct implications for the management of Histosols and is an important diagnostic criterion in their classification. '*Sapric*' peat consists for less than one-sixth of recognizable plant tissue after the material is gently rubbed. Such well-decomposed peat constitutes the body of many '*low moor peat*' formations (there are numerous exceptions!). '*Fibric*' peat consists for more than two-thirds of recognizable plant tissue (after rubbing) and constitutes the bulk of ombrogenous raised bogs. Here too, there are exceptions: raw and brittle mangrove peat is an example of fibric '*low moor peat*'. '*Hemic*' peat is intermediate between fibric and sapric peat.

Figure 4
Cross-section of a small coastal 'raised dome' formation near Pontianak, Indonesia. Note the fibric core of the ombrogenous dome, the better decomposed (hemic and sapric) shell, and the occurrence of sapric and clayey topogenous peat at the foot of the dome



Ombrogenous '*high moor peat*' in the Temperate Zone is mostly moss (*Sphagnum*) peat. The upper tiers of such 'dome' peat formations tend to be less decomposed than peat at some depth. This is in sharp contrast with raised (forest) peat formations in the wet tropics that are most decomposed in the top 10-30 cm layer. This difference is caused by the difference in botanical composition. *Sphagnum* has no root system and grows only at its top end. Base parts that become covered by new growth die off and become conserved in the acid and oxygen-poor water of the dome's core. By contrast, tropical raised bogs formed under swamp forest. The surface tier of such peat domes is aerated from time to time and is chemically enriched with nutrients through litter fall. All this promotes microbial activity and decomposition of the organic surface soil. Once this relatively well decomposed surface material becomes covered with younger peat in the course of further vertical growth of the bog, the water table rises (bogs are sponges!) and brings the former surface horizon within the permanently saturated zone (and below the zone of active nutrient cycling!). Decomposition of organic material is negligible in the permanently water-saturated subsurface soil while soluble and fine-grained insoluble organic matter is continually removed with effluent water. The result is a loose, coarse fibric and increasingly lignin/wood-rich skeletal core.

In horizontal direction there is similar differentiation. Permanently saturated central dome areas consist of peat that is less decomposed than comparable layers nearer to the fringe of the dome where the peat is younger, (relatively) rich in nutrients, occasionally aerated and subject to more intensive microbial attack. Figure 4 shows the different degrees of peat decomposition in a tropical raised bog.

CHARACTERISTICS OF HISTOSOLS

The exceptionally large total pore volume of Histosols (typically > 85%), their perishable nature and their normally poor chemical properties pose formidable problems to farmers and others concerned with conserving use of Histosols.

Morphological characteristics

Most Histosols have H or HCr profiles. Transformation of plant remains, through biochemical disintegration and formation of humic substances creates a surface layer of mould. Translocated organic material may accumulate in deeper tiers but is more often leached from the soil.

Hydrological characteristics

The central areas of virgin topogenous peat bodies and of ombrogenous formations in lowlands are nearly always saturated with near-stagnant water. The fringe areas of extensive raised bogs have a less monotonous water regime, with drier areas near natural depressions due to gravity drainage of the immediate surroundings. The opposite seems true for smaller domes where the water regime is less buffered. Radial drainage of such domes results in occasional floods near the margins while the center may at times be quite dry at the surface.

Physical characteristics

Fibric Histosols are loosely packed in their natural state, with a bulk density (ρ) that is typically between 0.05 and 0.15 Mg/m^3. Surface tiers of ombrogenous forest peat contain (still) more mineral 'ash' than the subsurface layers and are slightly denser (ρ -values of the order of 0.15 to 0.25 Mg/m^3). Reclaimed (drained and cropped) peat formations acquire a higher bulk density (say, 0.4 Mg/m^3) after a few years of consolidation and decomposition of peat.

The specific gravity (ρ_s) of organic soil material with a low content of mineral constituents (less than, say, 3 percent by weight) is nearly always close to 1.4 Mg/m^3. It follows that the total pore fraction (= 1-ρ /ρ_s) of most ombrogenous Fibric Histosols exceeds 0.9 m^3/m^3; skeletal subsurface tiers consist for only 5 to 10 volume percent of solid matter (sic!).

Fibric peat has many wide pores. Its saturated hydraulic conductivity is typically greater than 1.6 m/d and may well exceed 30 m/d. Well-decomposed *sapric* peat has finer pores and is less permeable. Virgin woody peat is nearly always very permeable to water; compacted (reclaimed/drained) peat has a much lower Total Pore Fraction than virgin peat. Compacted, stratified peat may be virtually impermeable, irrespective of its fiber content.

Table 1 presents total pore space (TPS) values calculated for the peat dome of Figure 4. Note the vertical and horizontal differentiation in packing density and its correlation with vegetation type.

The loose structure and flexible peat fibers account also for the low bearing capacity and poor trafficability of most peat formations. The low penetration resistance makes it difficult to use normal farm machinery and even light equipment may get stuck because of high rolling resistance and slip. The bearing capacity of a peat body is largely determined by the water content of the peat, and by internal friction and 'effective normal stress' (stress transmitted through the peat skeleton). The bearing capacity increases upon reclamation (consolidation) of the peat.

TABLE 1
Total Pore Fractions (TPF = 1 - ρ /ρ_s) calculated for a peat dome near Pontianak, Indonesia

VEG. TYPE		Mixed Swamp Forest (Dome fringe)	Transition	Monotonous Forest (Dome center)		
SITE (km) **		13	11.4	10.9	9.4	8.0
10-20 cm	ρ:	0.20	0.15	0.13	0.14	0.13
	ρ_s:	1.39	1.28	1.42	1.52	1.44
	TPF:	**0.86**	**0.88**	**0.91**	**0.91**	**0.91**
70-80 cm	ρ:	0.23*	0.11	0.10	0.10	0.09
	ρ_s:	1.67*	1.24	1.35	1.48	1.29
	TPF:	**0.86**	**0.91**	**0.93**	**0.93**	**0.93**

* Clayey peat from shallow fringe area
** See Figure 4.

Chemical characteristics

The wide variation in the physical characteristics of Histosols is matched by an equally wide variation in chemical properties. Chemically rich (or '*eutrophic*') low moor peat may have a field-pH greater than 6, whereas rain-dependent raised bogs are poor in plant nutrients and have field-pH values that are typically between 3 and 5.5. Extremely acid Histosols, with a field-pH value around 3, have been observed in coastal regions where pyrite (FeS_2) containing peat bogs were drained. Alkaline peat (field-pH around 7.8) has been reported from the Maldives.

The organic fraction of peat consists of *lignin*, *cellulose*, *hemicellulose* and small quantities of *proteins*, *waxes*, *tannins*, *resin*, *suberin*, etc. Ombrogenous moss peat in cold and temperate regions consists largely of cellulose whereas peat from deep lowland peat formations in Indonesia and Malaysia consists for two-thirds of lignin, with cellulose/hemicellulose accounting for only 1-10 percent of the dry sample weight.

Note that one important organic fraction in organic soil materials is not contained in fresh plant debris but is synthesized in the course of microbial transformation of the organic soil materials: '*humic substances*', a mixture of humins and humic and fulvic acids. Humic substances form stable complexes with metal ions. These are easily leached out of the peat mass with effluent water. (Geographic names such as 'Rio Negro', 'Blakkawatra', 'Cola Creek', 'Air hitam', 'Zwartewater' and many more, testify of the constant leaching of organic compounds from peat bogs.)

Table 2 presents ranges in the total microelement contents of virgin, deep and extremely poor Fibric Histosols in ombrogenous forest peat in Indonesia. The higher element contents of surface tiers reflect the cycling of elements by the vegetation.

TABLE 2
Microelement contents (kg/ha) of deep ombrogenous forest peat in Indonesia

	0 - 25 cm	80 - 100 cm
Cobalt	0.1-0.2	0.05-0.1
Copper	0.8-8.0	0.2-0.8
Iron	143-175	67-220
Manganese	4.1-25	1.1-7.1
Molybdenum	0.6-1.0	0.3-0.6
Zinc	2.8-4.4	1.8-4.8

Note that a considerable part of all nutrients/elements in the plant-soil-atmosphere system are stored in the vegetation; the values presented in Table 2 are by no means indicative of the total quantities present immediately after felling and burning of the (forest) vegetation.

The same holds true for the contents of macro- and secondary nutrients in the soil. In forest peat, nutrient levels are highest in the top 25 cm of the soil. Felling of the natural forest (part of the 'reclamation' process of peat lands) upsets this pattern because of interrupted nutrient cycling, release of nutrients from decaying organic materials, increased leaching of nutrients, volatilization upon heating (burning) of the peat, etc.

The quantities of nitrogen contained in the 0-20 cm surface tier of tropical ombrogenous forest peat are of the order of 2,000 to 4,000 kg N/ha, of which only a very small portion is readily 'available' to plants. Contents of 'total ash', K_2O, P_2O_5 and SiO_2 of the surface soil decrease sharply after clearing of the forest vegetation whereas CaO and MgO contents tend to increase. Quantities of Na, Cl and SO_4 in peat depend strongly on local conditions such as the distance to the sea and the presence or absence of pyrite in the peat.

Ombrogenous moss peat (in temperate regions) contains much less plant nutrients than forest peat that supports a far greater biomass with intensive cycling of nutrient elements.

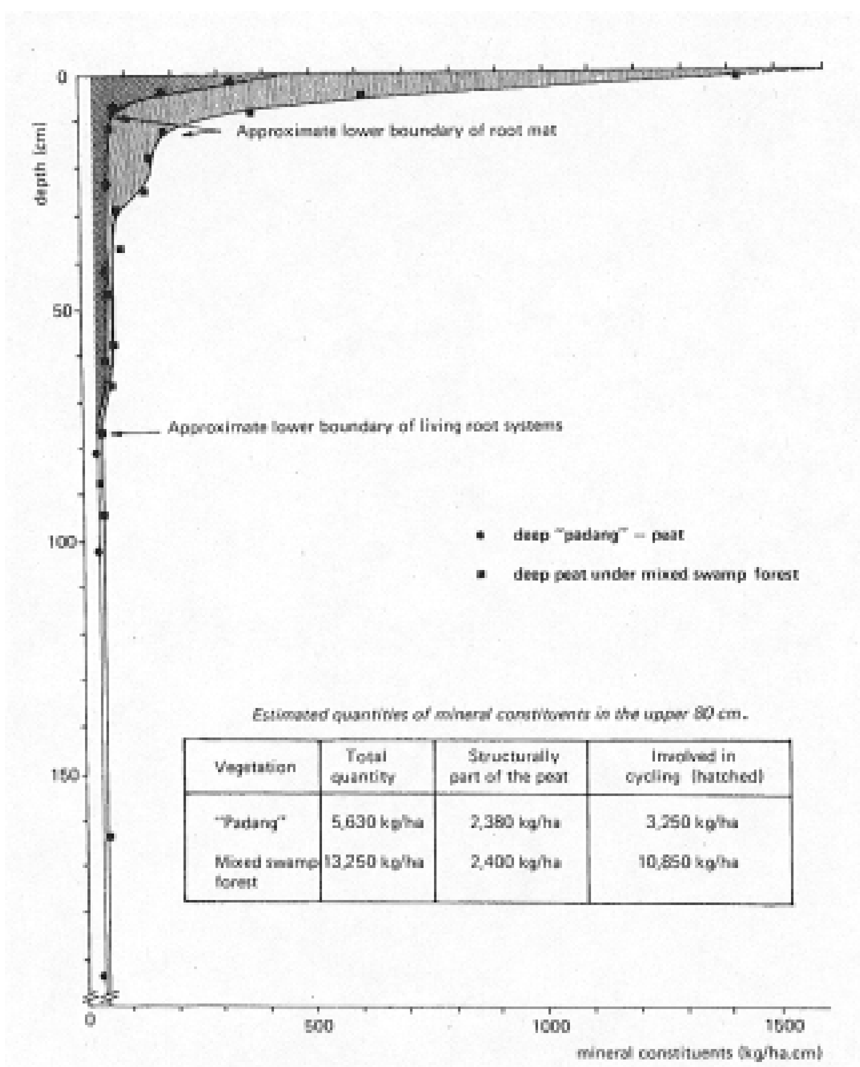
Figure 5 illustrates how nutrient elements in young and mature Fibric Histosols in (tropical) forest peat are concentrated in the upper 10 cm of soil where a dense root mat occurs. Living roots are absent (and 'ash' contents low) in deeper layers.

It is generally true that nutrient element levels are lowest in genetically old Histosols, with the exception of Rheic Histosols, which receive nutrients from outside and cannot be included in any generalized account of the chemical properties of peat soils.

Management/use of Histosols

The properties of the organic soil material (botanical composition, stratification, degree of decomposition, packing density, wood content, mineral admixtures, etc.) and the type of peat bog (basin peat, raised bog, etc.) determine the management requirements and use possibilities of Histosols. Northern Histosols are of little use for agriculture but they are part of a unique ecosystem and a habitat for many plant and animal species. In North America and northern Europe there is a growing tendency towards preservation and conservation of the delicate peat lands. Elsewhere more and more bogs are 'reclaimed'[1] for agriculture, horticulture and forestry.

Figure 5
Distribution of mineral constituents in two deep, virgin, ombrogenous forest peat formations in Kalimantan



Vegetation	Total quantity	Structurally part of the peat	Involved in cycling (hatched)
"Padang"	5,630 kg/ha	2,380 kg/ha	3,250 kg/ha
Mixed swamp forest	13,250 kg/ha	2,400 kg/ha	10,850 kg/ha

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[1] The word 'reclaimed' is a misnomer in this context; the peat is just 'claimed' and transformed.

Natural peat bogs must be drained and normally also limed and fertilized, to permit cultivation of 'normal' crops. Centrally guided reclamation projects are (almost) exclusive to the Temperate Zone where millions of hectares have been 'opened'. In many instances this initiated the gradual degradation, and ultimately the loss, of the precious peat. In the tropics, increasing numbers of landless farmers venture out into the peat lands where they clear the forest and cause raging peat fires in the process. Most of them abandon their land again after only a few years; the few who succeed are on shallow, topogenous peat. Since a few decades, increasing areas of tropical peat land are planted to oil palm and pulp wood tree species such as *Acacia mangium*, *Acacia crassicarpa* and *Eucalyptus sp*. This practice may be less than ideal but it is far less destructive than arable subsistence farming.

'Reclamation' of peat lands for agricultural uses starts nearly always with the construction of shallow drainage ditches. As a rule, the natural vegetation is left standing for a while because it accelerates drying of the peat. One-meter-deep drains at 20-40 m intervals are satisfactory in most cases but well decomposed or clayey peat may require narrower spacing. Woody dome peat formations could in some cases be drained with ditches 100 m apart. It is not advisable to install a complex drainage system right at the start of reclamation because uneven subsidence of the land surface is likely to disrupt the connections between sucker drains and collecting drains.

The drainage system will have to be adjusted after some time of operation because peat properties change. The soil's hydraulic conductivity might decrease in the course of drainage following the collapse of large pores, the formation of an illuvial horizon, or the effects of tillage. On the other hand, the soil may actually become more permeable after some time because of decaying wood providing passage for the escape of water or because of increasing biological activity (roots, animals) or the formation of cracks. In practice, draining peat lands is a matter of experience and standard formulas that are applicable to mineral soils are of little value. Farmers in the tropics prefer to use shallow, hand-dug drainage ditches that can be deepened as needed.

It is difficult to say exactly *when* peat reclamation is completed. Reclamation and cultivation overlap and in most instances cropping is even part of reclamation. In the case of forest peat, suitable annual crops may produce fair yields for a few years thanks to the nutrients that are still contained in the surface soil and in the (ashes of) decaying biomass. The uneven distribution of these nutrients over a field explains the irregular growth that is typical of young reclamation areas. After 3 or 4 years the peat has settled and subsidence of the land surface has slowed enough that trees and shrubs can be planted. These may grow satisfactorily for some time but yields will eventually decrease if the land is not fertilized.

Small farmers sometimes resort to some sort of 'controlled' burning of the peat to 'liberate' nutrients and to raise the pH of the surface soil. Burning has undoubtedly a stimulating effect on plant growth but the desirability of burning and its precise effects are still open to discussion. Those in favour of controlled burning claim that it is not more destructive than oxidation in the long run but concentrates certain nutrients (N, P, K, Ca, Mg, S) in the surface soil and renders them more available to the plant. Others are of the opinion that burning should be discouraged altogether because most of the liberated nitrogen and sulphur are lost to the atmosphere and other nutrients are largely leached out of the surface soil. The overall deterioration of the soil structure (the burnt layer is usually by far the richest part of the profile) and the resulting uneven soil surface are additional arguments against burning.

The difficulties that confront farmers on Histosols become evident if one considers the differences in 'plant engineering' between 'normal' crops and the native peat swamp vegetation. The latter is adapted to an environment with prolonged water-saturation, strong acidity, oligotrophy and/or noxious levels of salt or other toxins. Such conditions made it possible that organic soil material could accumulate but they are incompatible with the needs of most crops.

Most arable crops need a deep, moist (not wet), well-aerated soil for development of a healthy root system. This means that the peat must be drained. Drainage affects the peat in several ways:

- Drained peat will consolidate as a consequence of '*settlement*' of the peat mass once the buoyancy of the water in water-saturated natural peat is removed: the peat mass settles under its own weight. Consolidation of the peat is enhanced by '*shrinkage*' of flexible peat fibers that collapse under the capillary forces, which develop when the peat is drained. Consolidation of drained peat is initially rapid but becomes gradually less felt as the bulk density (r) of the soil mass increases. Consolidation causes loss of drained soil *volume* and subsidence of the land surface. This means that the depth of drains must be regularly adjusted to maintain freeboard and healthy root growth. Increasing the drainage depth will again accelerate consolidation, and loss of surface elevation, until – after a number of successive adjustments that accelerate consolidation ever less strongly – a situation of near-stability is reached. As a rule of thumb, this happens when the dry bulk density of the soil mass has become close to $r = 0.4\ Mg/m^3$.

- Aeration of peat accelerates the rate of microbial decomposition of the peat ('*mineralization*'). In contrast with consolidation, mineralization is an ongoing process; it causes both loss of peat *volume* and loss of peat *mass*. The rate of mineralization increases after liming and/or fertilization of the soil. Mineralization rates reported for 'reclaimed' tropical forest peat planted to horticultural crops, with liming and full fertilizer application, are as high as 10 cm/year; *net* mineralization losses under plantation forest (*Acacia sp.*), with a closed canopy and much greater leaf fall than horticultural crops, are probably negligible. Liming and fertilization are indispensable for good yields but enhance the rate of peat mineralization. Ombrogenous peat in particular requires massive applications of lime or ground (magnesium) limestone to raise the pH of the soil to a level that permits satisfactory crop production. Normally, full fertilization with N-P-K fertilizers must be combined with application of small quantities of sulfur, copper, zinc, manganese, molybdenum and iron.

Reclamation of Histosols has also indirect effects. Some are favourable, others are not:

- The initially low packing density (and high Total Pore Volume) of newly reclaimed Histosols is associated with poor accessibility and trafficability of the peatland and with poor anchorage of crops. Uneven subsidence of the land and leaning and tree fall are prominent in young reclamation areas. When peat consolidates after drainage, its packing density increases. The rate of peat mineralization slows down as the fraction of easily decomposable organic compounds in the surface peat decreases relative to the fractions of 'stable humus' and 'ash'. All of this results in a denser and more stable peat body, that is better trafficable, provides better anchorage to plant roots and is less prone to loss of surface peat (and exposure of lateral roots).

- Strong desiccation of organic soil material may drastically and irreversibly alter its colloidal properties. Loss of organic soil material by wind erosion is a problem in areas with deeply drained Histosols, particularly in the Temperate Zone. Plowing such soils produces huge clouds of peat dust that can be seen from far away. Overheating of deeply drained forest peat e.g. where newly opened tropical peat is exposed to direct sunlight, converts valuable surface peat into dry, hydrophobic granules and dust that are highly susceptible to both water and wind erosion.

In summary, peat lands must be protected and conserved because of their intrinsic value and because prospects for sustained agricultural use are meager. If they must be used for plant production, sensible forms of forestry or plantation cropping are to be preferred over annual cropping, horticulture or, the ultimate nightmare, 'harvesting' of the peat material for power generation or 'production' of horticultural growth substrate, 'active carbon', flower pots, etc. Peat lands that are used for arable crop production will mineralize at sharply increased rates because they *must* be drained, limed and fertilized to ensure satisfactory crop growth. It is particularly important to conserve the peat if loss of surface elevation may mean loss of land. This danger is real e.g. where the underlying mineral substratum is below the general drainage basis (e.g. the current river level) and/or where the peat has poor agricultural properties (e.g. contains potentially acid 'pyritic' marine sediment).

Set #2

Mineral Soils conditioned by Man

Anthrosols

ANTHROSOLS (AT)

The Reference Soil Group of the Anthrosols holds soils that were formed or profoundly modified through human activities such as addition of organic materials or household wastes, irrigation or cultivation. The group includes soils otherwise known as 'Plaggen soils', 'Paddy soils', 'Oasis soils' and 'Terra Preta do Indio'.

Definition of Anthrosols[#]

Soils having
1. a *hortic*[@] , *irragric*[@], *plaggic*[@] or *terric*[@] horizon 50 cm or more thick; or
2. an *anthraquic*[@] horizon and an underlying *hydragric*[@] horizon with a combined thickness of 50 cm or more.

Common Soil Unit qualifiers:
1. *Units characterizing the surface horizon*: Hydragric*, Irragric*, Terric*, Plaggic*, Hortic*.
2. *Units characterizing buried horizon(s) or soil*: Gleyic*, Spodic*, Ferralic*, Luvic*, Arenic*, Regic*, Stagnic*.

\# See Annex 1 for Key to all Reference Soil Groups.
@ Diagnostic horizon, property or material; see Annex 2 for full description.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Anthrosols

Connotation: soils with prominent characteristics that result from human activities; from Gr. *anthropos*, man.

Parent material: virtually any soil material, modified through cultivation or by addition of material.

Environment: Plaggic Anthrosols are most common in north-west Europe; Hydragric Anthrosols in Southeast and East Asia, and Irragric Anthrosols in the Middle East.

Profile development: the influence of Man is normally restricted to the surface horizon(s); the horizon differentiation of a buried soil can still be intact at some depth.

Use: European Anthrosols were traditionally grown to winter rye, oats, and barley but are now also planted to forage crops, potatoes and horticultural crops; in places they are used for tree nurseries and pasture. Irragric Anthrosols occur in irrigation areas where they are under cash crops and/or food crops. Hydragric Anthrosols are associated with paddy rice cultivation whereas Hortic Anthrosols are (mainly) planted to vegetables for home consumption.

Regional distribution of Anthrosols

Anthrosols are found wherever people have lived for a long time. Plaggic and Terric Anthrosols extend over more than 500,000 hectares in north-western Europe (See Figure 1). Irragric Anthrosols are found in irrigation areas in dry regions, e.g. in Mesopotamia and in parts of India. Hydragric Anthrosols (*'paddy soils'*) occupy vast areas in China and in parts of South and Southeast Asia (e.g. Sri Lanka, Vietnam, Thailand, and Indonesia). Hortic Anthrosols are found all over the world where Man has fertilized the soil with household wastes and manure. The '*Terra Preta do Indio*' in the Amazon Region of Brazil belong to this group.

Figure 1
Plaggic and Terric Anthrosols in northwestern Europe. Source: Pape, 1970

Associations with other Reference Soil Groups

Anthrosols occur in association with a wide variety of Reference Soil Groups. Some well-known lateral linkages:

- *Plaggic Anthrosols* are associated with infertile Arenosols and Podzols in areas with periglacial cover sands in western Europe.
- *Terric Anthrosols* are commonly found alongside wetland soils such as Fluvisols, Gleysols and Histosols or with acid/unfertile Albeluvisols, Arenosols or Podzols.

- *Irragric Anthrosols* are associated with typical soils of dry regions such as Calcisols, Gypsisols, Solonchaks and Solonetz, and with Regosols and Cambisols.
- *Hydragric Anthrosols* occur together with Gleysols and Fluvisols in river systems, with Alisols, Acrisols, Lixisols and Luvisols in upland areas and with Andosols in volcanic regions.
- *Hortic Anthrosols* can occur alongside virtually any Reference Soil Group.

Genesis of Anthrosols

Anthrosols have formed as a result of long-continued '*anthropedogenic processes*', notably

1. *deep working*, i.e. below the normal depth of tillage (e.g. in terraced lands in the Mediterranean Region, the Arab Peninsula, the Himalayas and the Andes);
2. *intensive fertilization* with organic/inorganic fertilizers *without* substantial additions of mineral matter (e.g. manure, kitchen refuse, compost, night soil);
3. *continuous application of earth* (e.g. sods, beach sand, shells, earthy manures);
4. *irrigation* adding substantial quantities of sediment;
5. *wet cultivation* involving puddling of the surface soil and man-induced wetness.

Note that soils consisting of unaltered '*anthropogenic soil material*' (i.e. unconsolidated mineral or organic material resulting from land fills, mine spoil, urban fill, garbage dumps, dredgings, etc.) do not qualify as Anthrosols. Such materials lack evidence of pedogenetic change. Soils in anthropogenic soil materials form a separate group within the Regosols, viz. the Anthropic Regosols.

Plaggic Anthrosols

Plaggic Anthrosols have the characteristic '*plaggic horizon*' produced by long-continued addition of 'pot stable' bedding material, a mixture of organic manure and earth. The man-made character of the plaggic horizon is evident from fragments of brick and pottery and/or from high levels of extractable phosphorus (more than 250 mg P_2O_5 per kg by 1 percent citric acid).

The formation of (most) plaggic horizons started in medieval times when farmers applied a system of 'mixed farming' combining arable cropping with grazing of sheep and cattle on communal pasture land. During nights and in wintertime, sheep and cattle were kept in stables with bedding material of thin sods of heath and/or forest litter. Fresh bedding material was regularly provided until the bedding became too thick and had to be removed. It was then spread out on the arable fields as an 'organic earth manure'. This addition of organic earth manure raised the surface level of (only!) arable fields by some 0.1 cm per annum. In places, the system was in use for more than a thousand years, evidenced by a plaggic horizon of more than 1 meter in thickness.

Depending on the composition of the bedding material, the plaggic horizon is black (bedding material from heath lands with Podzols) or brown (from forest litter) in colour. In places, sods from low-lying grasslands were incorporated in the earth manure. This gave the A-horizon a somewhat higher clay content than the deeper solum. Historical records indicate that some 10 hectares of heath land were needed to maintain the nutrient level of one hectare of arable land. Removal of the sods made the heath land susceptible to wind erosion; large tracts of heath land turned to barren shifting sands that went completely out of control (see also under Arenosols).

By and large, arable fields were situated on favourable sites that were well-drained even before acquiring a plaggic horizon. Winter rye on such locations is less susceptible to frost damage; only in densely populated areas were less well-drained soils used for arable cropping. The configuration of arable fields at higher terrain positions and pastures in nearby depressions can still be seen today. The mixed farming system described produced the world's largest continuous area of Plaggic Anthrosols (see Figure 1).

Note that other types of plaggic horizons occur as well, formed for instance by gradually covering peat soils with layers of bagger from drainage ditches with or without additions of organic manure.

Terric Anthrosols

In parts of western Europe, notably in England and Ireland, calcareous soil materials (e.g. beach sands) were carted to areas with acid Arenosols, Podzols, Albeluvisols and Histosols. Eventually these soils turned into Terric Anthrosols with a man-made surface layer of mineral soil material that has far better properties for arable cropping than the original surface soil.

Irragric Anthrosols

Irragric Anthrosols are formed as a result of prolonged sedimentation of silt from irrigation water. A special case are Irragric Anthrosols in depression areas where dryland crops are commonly planted on man-made ridges that alternate with drainage furrows. The original soil profile of the ridge areas is buried under a thick layer of added soil material. The ridge-and-furrow system is known from such different environments as the lowland forests of Western Europe and the coastal swamps of southeast Asia where the ridges are planted to dryland crops and rice is grown in the shallow ditch areas (see also the chapter on Fluvisols).

Hydragric Anthrosols

Hydragric Anthrosols are the result of long-continued wet cultivation. "Puddling" of wetland rice fields (involving destruction of the natural soil structure by intensive tillage when the soil is saturated with water) is done intentionally, *inter alia* to reduce percolation losses. Puddling makes the surface soil dispersible and produces a surface layer that has uniform aggregates and predominantly vesicular pores when dry. The colour of the puddled layer and low hue mottles and iron-manganese cutans on ped faces and pore walls testify of prolonged reduction of the soil material. In the course of time, a plough pan develops underneath the puddled layer; it has a platy structure and is much denser than the puddled layer.

Together, the puddled layer and the plough pan constitute the '*anthraquic horizon*'. Horizons below the anthraquic horizon are modified by redoximorphic processes and show differentiated zones of iron and manganese that percolated downward from the anthraquic horizon.

Hortic Anthrosols

Hortic Anthrosols are "kitchen soils". The Hortic Anthrosols on river terraces in southern Maryland, U.S.A., and along the Amazon River in Brazil are well-known examples. These soils have deep, black surface horizons formed in layers of kitchen refuse (mainly oyster shells, fishbones, etc.) from early Indian habitation. Many countries possess small areas of soils that were modified by early inhabitants.

Characteristics of Anthrosols

Morphological characteristics

Anthrosols are differentiated by their anthraquic, hortic, hydragric, irragric, terric or plaggic surface horizon. Horizons of an underlying buried soil may have become incorporated in the – now - Anthrosol. In some cases (notably in Plaggic or Terric Anthrosols) evidence of human activity such as spade marks is still detectable.

Hydrological characteristics

Plaggic and Terric Anthrosols are well-drained because of their thickened A-horizon; most Irragric Anthrosols have an active soil fauna and good porosity. Iron-manganese mottles may be present but are not necessarily indicative of inadequate internal soil drainage; they could just as well be caused by over-irrigation. Hydragric Anthrosols possess a man-made impervious plough pan and are periodically flooded as part of the cropping system. Hortic Anthrosols are well-drained, particularly those near villages that were established on higher grounds; some have developed from wetland soils and have restricted internal drainage.

Physical characteristics

The physical characteristics of plaggic and terric horizons are excellent: penetration resistance is low and permits unhindered rooting, the pores are of various sizes and interconnected and the storage capacity of 'available' soil moisture is high if compared to that of the underlying soil material. 'Mild' organic matter in the surface soil stabilizes the structure of the soil and lowers its susceptibility to slaking. The upper part of a plaggic or terric horizon may become somewhat dense if tillage is done with heavy (vibrating) machinery.

Most irragric horizons have little organic matter but many have an active soil fauna. Silty Irragric Anthrosols have good water-holding properties but clayey soils tend to become massive and very hard when dry, and are difficult to till. Hortic horizons are very porous on account of their intense biological activity (characteristically, hortic horizons contain more than 25% earthworm casts), and their high organic matter content.

Chemical characteristics

Plaggic horizons are more acid (pH_{KCl} between 4 and 4.5) and contain more organic carbon (1 – 5 %) than terric horizons. By and large, *black* plaggic horizons contain more organic matter than *brown* ones; the C/N ratio is generally between 10 and 20, with the higher values in black soils. Reported CEC values are between 5 and 15 cmol(+)/kg soil; the 'total' phosphorus content is high.

Irragric horizons have high base saturation; they may contain free lime and can even be alkaline in reaction. Some irragric horizons are saline as a result of accumulation of salts that were dissolved in the irrigation water.

Anthraquic horizons have a (near) neutral soil reaction when submerged. Under reducing conditions, Fe^{2+} and Mn^{2+} may be present in toxic quantities.

Most hortic horizons have a good CEC, acquired after long-continued application of organic residues, and are well supplied with nutrients. They have a phosphorus content (0.5M $NaHCO_3$ extractable P_2O_5) of more than 100 mg/kg soil.

Management and use of Anthrosols

Plaggic Anthrosols

Plaggic Anthrosols have favourable physical properties (porosity, rootability, moisture availability) but many have somewhat unsatisfactory chemical characteristics (acidity, nutrients). Rye, oats, barley, potato and also the more demanding sugar beet and summer wheat are common crops on Plaggic Anthrosols in Europe. Prior to the advent of chemical fertilizers, rye yields on Plaggic Anthrosols were a mere 700 to 1100 kg per hectare, or 4 to 5 times the quantity of seed used. Today, these soils receive generous doses of fertilizers; average yield levels are 5000 kg rye per hectare, 4500 kg barley and some 5500 kg summer wheat. Sugar beet and potato produce 40 to 50 tons per hectare. Plaggic Anthrosols are increasingly used for production of silage maize and grass; in Europe, 12 to 13 tons of dry maize silage per hectare and 10 to 13 tons of dry grass are considered normal.

Plaggic Anthrosols are also used for tree nurseries and horticulture. The good drainage and the dark colour of the surface soil (early warming in spring) make it possible to till and sow or plant early in the season. Soils with deep plaggic horizons in The Netherlands were in demand for the cultivation of tobacco until the 1950's.

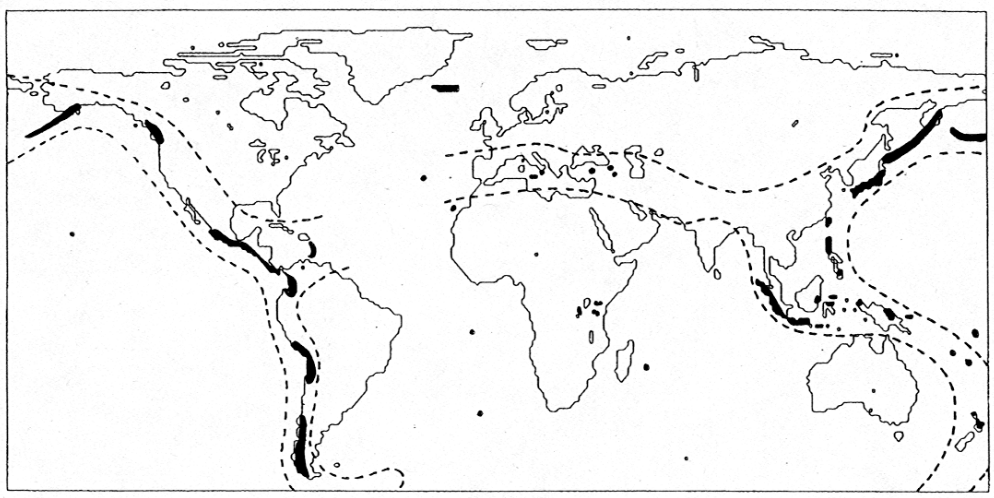
Set #3

Mineral Soils conditioned by Parent Material

Major landforms in volcanic landscapes

Volcanism is not randomly distributed over the world. It is concentrated near plate boundaries where plate subduction or seafloor spreading takes place. Other occurrences are linked to deep mantle plumes that reach the Earth's surface at distinct '*hotspots*'. Figure 1 shows the geographic distribution of major volcanic regions.

Figure 1
Major volcanic regions of the world

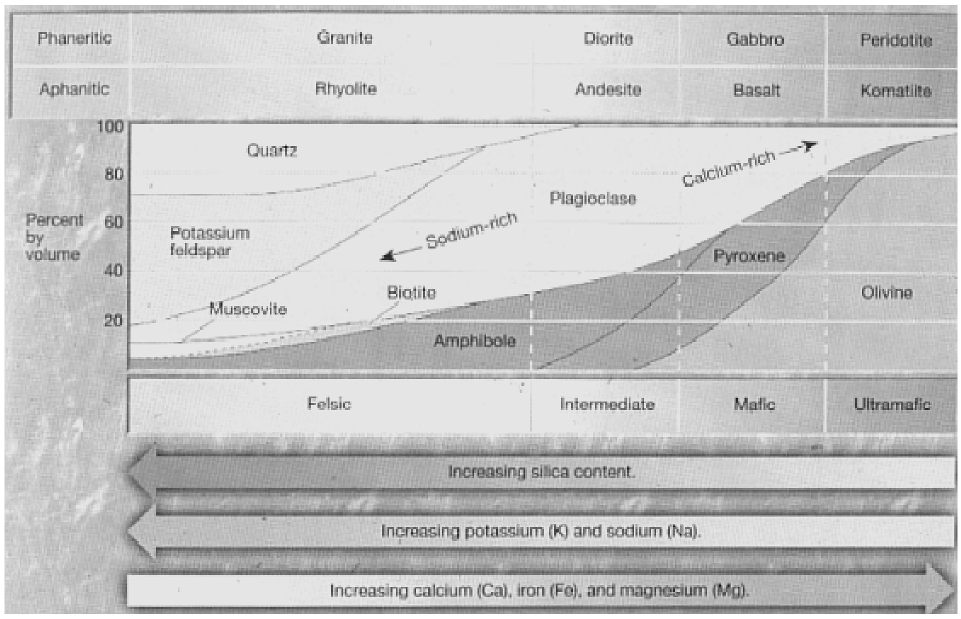


Landforms in volcanic regions are strongly influenced by the chemical and mineralogical composition of the materials that were deposited during eruptive phases. Volcanic rocks and magmas are grouped according to their silica contents in three main categories labeled '*Rhyolite*' (65-75% SiO_2), '*Andesite*' (65-55% SiO_2) and '*Basalt*' (55-45% SiO_2). The mineralogical properties and chemical composition (notably the contents of K2O, Na2O and CaO) distinguish individual rock types. See Figure 2.

The broad division of volcanic rocks and magmas on the basis of silica content makes sense because the SiO_2 content correlates with the viscosity of magmas and hence with the type of volcanism. A rule of thumb: the higher the silica content of magma is, the more acid and viscous the magma is and the more explosive volcanic eruptions are. This influences profoundly the character and morphology of volcanic phenomena.

In the following, major landforms of volcanic regions will be discussed taking magma composition as a reference point.

Figure 2
Chemical and mineralogical properties of major volcanic rock types



Major landforms in regions with basaltic volcanism

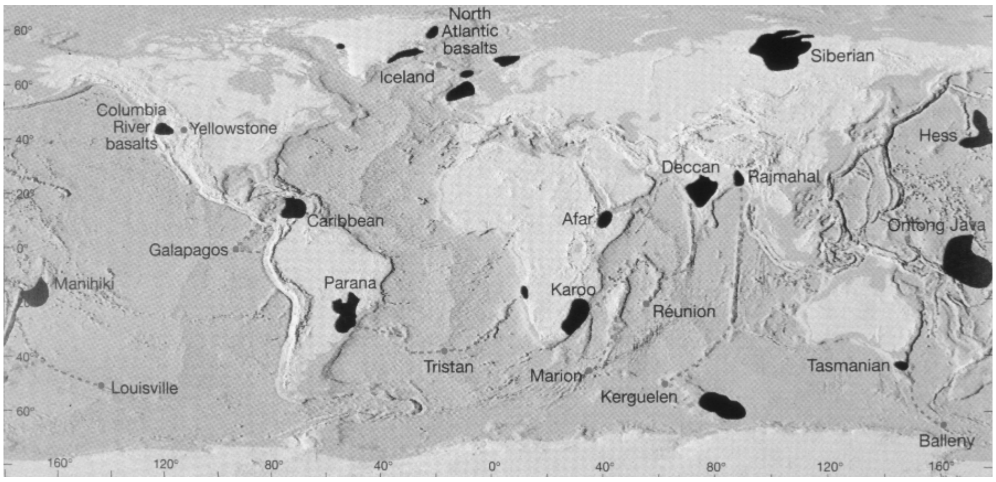
Basaltic volcanism occurs where basic mantle material reaches the surface, notably

1. at *divergent plate margins* (sea floor spreading),
2. in *'hot-spot' areas*, and
3. in *continental rift valleys*.

Re 1: The best-known divergent plate margin is the mid-oceanic ridge or rise. The highest parts of the ridge may reach the surface of the ocean and form islands, e.g. Iceland and the Canary Islands. It is not surprising that, like all ocean floors, Iceland consists mainly of basaltic rock.

Re 2: A fine example of basaltic hot-spot volcanism is Hawaii, which constitutes the top of the largest '*shield volcano*' in the world, with a diameter of 250 km at the base (on the ocean floor) and a total height of 9 km. Basaltic magma is little viscous and gases escape easily. Eruptions are therefore relatively quiet and produce low-viscosity lava flows, lava lakes and lava fountains, but little ash. The fluid magma can flow over large distances and the resulting shield volcanoes are comparatively flat. Most eruptions are '*fissure eruptions*' that take place along extensional cracks in the Earth's crust. The fissures may be several kilometers in length; the historical 'Laki' eruption on Iceland happened along a 24-km long fissure. Much bigger fissure eruptions have taken place in the past. They produced enormous masses of '*flood basalt*' that covered hundreds of square kilometers. The Parañа plateau in South America is made up of 1 million km^3 basalt, which was extruded within 10 million years. Other examples of large occurrences of flood basalt are in Ethiopia, Siberia, Greenland, Antarctica, India (the 'Deccan Traps') and in the western USA (Colombia River). See Figure 3.

Figure 3
World-wide occurrence of flood basalts



Re 3. Many hotspots that are situated below a continental crust are associated with mantle plumes that push the crust up ('*updoming*') and cause large-scale dilation cracks. The latter become manifest as elongated tectonic depressions: the rift valleys. Both basic (SiO_2 poor) and acid (SiO_2 rich) volcanism occur in and along rift valleys. Basaltic volcanism in continental rift valleys (e.g. the East-African rift valley, the Baikal graben, or the Rhine-Rhone graben) is associated with '*strombolian*' scoria cones and with '*maar*' craters (i.e. steam-explosion craters now filled with water). Here too, ash deposits seldom extend beyond the volcanic areas themselves. Where ash blankets are extensive, as in some rift valleys, they are usually more acidic.

The comparatively fluid basaltic lava flows tend to follow river valleys and can flow over considerable distances into the rift valley. Subsequent erosion of soft sediments adjacent to the lava bodies results in 'relief inversion', with the former basaltic valley fills extending as elongated plateaus in the eroded landscape.

Landforms in regions with andesitic volcanism

Andesitic volcanism is a characteristic element at convergent plate boundaries where plate subduction takes place. Typical settings are

1. *'Cordillera'-type mountain belts* (like the Andes), and
2. *island arcs* (e.g. the Philippines and Japan).

The classic volcano type associated with andesitic volcanism is the '*stratovolcano*'. Literally, the term means 'stratified' volcano, which is misleading in the sense that all volcanoes are built up of layers, be it of basalt flows, as in the Hawaiian shield volcanoes, or of pyroclastics, as the scoria cones of the Eifel. What the term indicates, actually, is that this type of volcano is composed of alternating layers of lava and pyroclastic rock, mostly of andesitic composition. Most stratovolcanoes are much larger than scoria cones and have a long history of alternating lava and pyroclastic rock eruptions.

Andesitic magmas hold an intermediate position between basaltic and rhyolitic magmas with respect to their SiO_2 content, viscosity and gas content. Whereas basaltic, low viscosity magmas hardly produce pyroclastics (*'tephra'*), and high-viscosity rhyolites hardly produce lavas, andesitic magmas will normally produce both. Because of the greater viscosity of the magma, greater pressure must build up before an eruption can occur; eruptions are less frequent and more violent than in basaltic volcanism.

Lava flows emitted by stratovolcanoes are more viscous than those of basaltic shield volcanoes, and do not extend as far from the point of emission, usually only a few kilometers. This explains why stratovolcanoes have steeper slopes than shield volcanoes and the 'classical' cone shape.

Active, large and high stratovolcanoes are likely to produce devastating volcanic mudflows (also called '*lahars*'). Lahars can form in several ways:

1. because the wall of a crater lake collapses during an eruption, or
2. because condensation nuclei in the air (volcanic ash) generate heavy rains (e.g. Pinatubo, Philippines 1992), or
3. because the volcano was covered with snow or glaciers before the eruption (e.g. Nevado del Ruiz, Colombia, 1985), or
4. because heavy rainfall following an eruption washes fresh ash deposits away.

'Pyroclastic flows' are frothy masses of ash and pumice. They evolve when an extrusive dome collapses, generating a fast moving avalanche of hot gases, ash and pumice. The resulting rocks are known as '*ignimbrites*' and can have a variety of structures depending on the flow conditions during emplacement and on the degree of post-depositional welding.

'Volcanic ash fall-out' often spreads far beyond the direct vicinity of the erupting volcano. Lava and pyroclastic flows are normally confined to the immediate vicinity of volcanoes but ashes can be blown into the troposphere and stratosphere, and can travel hundreds of kilometers. The thickness of the ash deposits decreases with increasing distance from the point of origin. It may be difficult to recognize the presence of volcanic ash in soils because it is incorporated in the solum, overgrown by vegetation and it weathers rapidly. Nonetheless, '*rejuvenation*' of soil material with fresh volcanic ash is often of great importance as it restores or improves soil fertility and promotes physical soil stability.

Landforms in regions with rhyolitic volcanism

Acid *'rhyolitic'* magmas are produced by partial melting of the continental crust, e.g. in cordilleran mountain ranges and rift valleys. Rhyolitic magmas are viscous and withstand very high gas pressures. As a result, rhyolitic eruptions are rare, but also extremely violent. If a rhyolitic magma chamber is present below a stratovolcano, tremendous gas pressures build up so that, once a vent for eruption is opened, the magma chamber empties itself completely, leaving a cavity in the Earth's crust in which the entire stratovolcano collapses. Craters of several kilometres in diameter are formed in this way: the '*calderas*' (e.g. Krakatoa in Indonesia; Ngorongoro in Tanzania; Crater Lake in the USA and the Laacher See in Germany). Only occasionally do more quiet eruptions take place. The high viscosity of the lava precludes lava flow; a lava dome is formed instead (e.g. Obsidian Dome, USA).

The main extrusive products of rhyolitic volcanism are:

1. *ashes*, in astonishing quantities and spread over vast areas, and
2. *ignimbrites* that stem from pyroclastic flows extending over several tens of kilometers and fill in depressions and valleys of tens or even hundreds of meters depth. In contrast with the irregular surfaces of lava flows and lahars, ignimbrite surfaces are flat and featureless. White, porous and fibrous pumice inclusions are common.

Both ashes and ignimbrites consist for the greater part of volcanic glass and weather easily. Crystals of (mainly) quartz and/or feldspars, biotite and hornblende ('*phenocrysts*'; Du.: '*eerstelingen*') make up less than 20 percent of the ash. The only historic ignimbrite-forming eruption was that of the Katmai in Alaska in 1912. The largest eruption in comparatively recent times took place some 40,000 years ago and led to the formation of Lake Toba on Sumatra, Indonesia.

Volcanic rocks especially pyroclastic rocks, contain volcanic glass that weathers easily and accounts for the remarkable properties that soils in most volcanic regions have in common. Translocations of weathering products and accumulation of short-range-order minerals and of stable organo-mineral complexes are essential processes in the formation of the characteristic soils of volcanic regions: Andosols.

ANDOSOLS (AN)

The Reference Soil Group of the Andosols holds soils developed in volcanic materials. Common international names are 'Andosols' (FAO, Soil Map of the World), 'Andisols' (USDA Soil Taxonomy), 'Andosols' and 'Vitrisols' (France) and 'volcanic ash soils'.

Definition of Andosols[#]

Soils having
1. a *vitric*[@] or an *andic*[@] horizon starting within 25 cm from the soil surface; and
2. no diagnostic horizons (unless buried deeper than 50 cm) other than a *histic*[@], *fulvic*[@], *melanic*[@], *mollic*[@], *umbric*[@], *ochric*[@], *duric*[@] or *cambic*[@] horizon.

Common soil units:
Vitric*, Silandic*, Aluandic*, Eutrisilic*, Melanic*, Fulvic*, Hydric*, Histic*, Leptic*, Gleyic*, Mollic*, Duric*, Luvic*, Umbric*, Arenic*, Placic*, Pachic*, Calcaric*, Skeletic*, Acroxic*, Vetic* , Sodic*, Dystric*, Eutric*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups.
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Andosols

Connotation: black soils of volcanic landscapes; from Jap. *an*, black, and *do*, soil.

Parent material: mainly volcanic ash, but also tuff, pumice, cinders and other volcanic ejecta.

Environment: undulating to mountainous, humid, arctic to tropical regions with a wide range of vegetation types.

Profile development: AC- or ABC-profile. Rapid weathering of porous volcanic material resulted in accumulation of stable organo-mineral complexes and short-range-order minerals such as *allophane*, *imogolite* and *ferrihydrite*.

Use: many Andosols are intensively cultivated and planted to a variety of crops, their major limitation being their considerable capacity to render phosphorus unavailable to plants. In places, steep topography is a serious constraint.

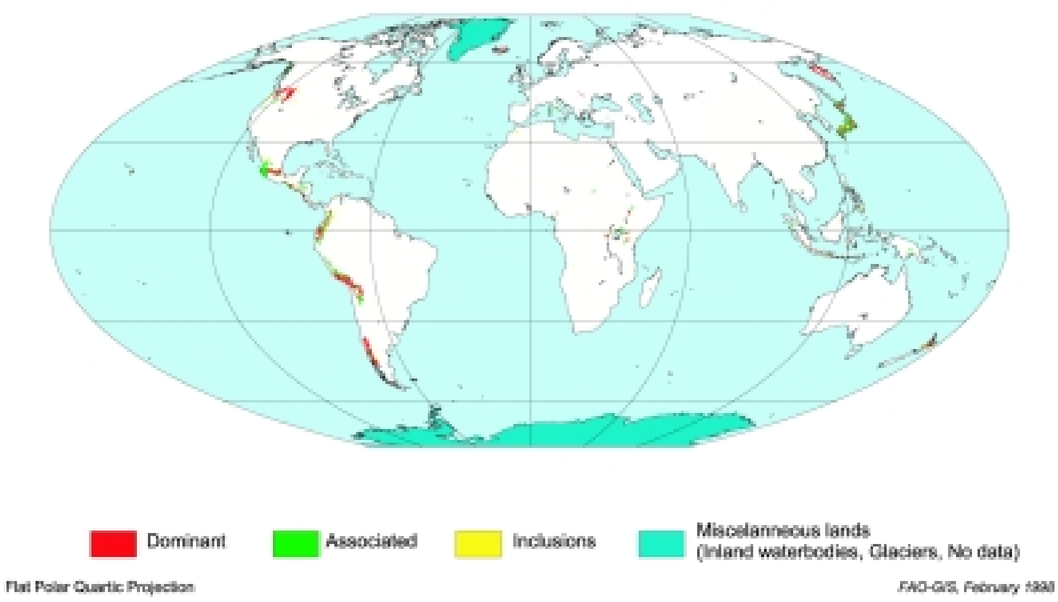
Regional distribution of Andosols

Andosols occur in volcanic regions all over the earth. Major concentrations are found around the Pacific rim: on the west coast of South America, in Central America, the Rocky Mountains, Alaska, Japan, the Philippine Archipelago, Indonesia, Papua New Guinea and New Zealand.

Andosols are also prominent on many islands in the Pacific: Fiji, Vanuatu, New Hebrides, New Caledonia, Samoa and Hawaii.

In Africa, Andosols are prominent along the Rift Valley, in Kenya, Rwanda and Ethiopia and on Madagascar. In Europe, Andosols occur in Italy, France, Germany and Iceland. The total Andosol area is estimated at some 110 million hectares or less than 1 percent of the global land surface. More than half of this is situated in the tropics. Figure 1 presents the world-wide distribution of Andosols. *Note that* the small scale of this map permits to show only the largest Andosol areas.

Figure 1
Andosols world-wide



Associations with other Reference Soil Groups

Andosols are *azonal* soils found in all climates and at all altitudes. Consequently they occur together with almost any other Reference Soil Group. A typical configuration on mountain slopes would have Andosols at the higher end of the slope, *Cambisols* and *Luvisols* at mid-slope positions and *Vertisols* (basic volcanic materials) or *Acrisols* (acidic materials) near the foot of the slope. In tropical highlands, e.g. in Kenya and Ethiopia, Andosols are often associated with *Nitisols*.

Genesis of Andosols

Andosols are characterised by the presence of either an '*andic*' horizon or a '*vitric*' horizon. An andic horizon is rich in '*allophanes*'[1] (and similar minerals) or aluminium-humus complexes whereas a vitric horizon contains an abundance of '*volcanic glass*'.

[1] *allophanes* are non-crystalline (short-range-order) hydrous aluminosilicates with Al/Si molar ratios typically between 1 and 2 (the Al/Si ratio of kaolinite is 1). They consist of hollow spherules with a diameter of 3.5 - 5 nm and have a very large (reactive) specific surface area.

Andosol formation depends essentially on rapid chemical weathering of porous, permeable, fine-grained mineral material in the presence of organic matter. Hydrolysis of the primary minerals *'microcline'* and *'augite'* may serve to illustrate this type of weathering ('glass' is actually an amorphous mixture but reacts in the same way):

$$KAlSi_3O_8 + 2\ H_2O\ =\ K^+ + Al^{3+} + 3\ SiO_2 + 4\ OH^-$$
microcline

$$CaFeSi_2O_6 + 2\ H_2O\ =\ Ca^{2+} + Fe^{2+} + 2\ SiO_2 + 4\ OH^-$$
augite

The liberated Fe^{2+} and (particularly) Al^{3+} ions are tied up in stable complexes with humus. The ferrous iron is first oxidised to the ferric state after which it precipitates for the greater part as *ferrihydrite*[2]:

$$Fe^{2+}\ =\ Fe^{3+} + e^-$$

$$Fe^{3+} + 3\ H_2O\ =\ \underset{\textit{ferrihydrite}}{Fe(OH)_3} + 3\ H^+$$

$$(\text{or: } 2\ Fe^{2+} + {}^1/_2\ O_2 + 5\ H_2O\ =\ 2\ Fe(OH)_3 + 4\ H^+)$$

Aluminium protects the organic part of Al-humus complexes against bio-degradation. The mobility of these complexes is rather limited because rapid weathering yields sufficient Al and Fe to produce complexes with a high metal/organic ratio that are only sparingly soluble. This combination of low mobility and high resistance against biological attack promotes accumulation of organic matter in the topsoil culminating in the formation of a '*melanic*' surface horizon that has an intense dark colour and a high content of organic matter.

The fate of the liberated silica is largely conditioned by the extent to which aluminium is tied up in Al-humus complexes. If most or all aluminium is 'fixed', the silica concentration of the soil solution increases and while part of the silica is washed out, another part precipitates as opaline silica. If *not* all aluminium is tied up in complexes, the remainder may co-precipitate with silicon to form allophanes of varying composition, often in association with *imogolite*[3].

Note that formation of Al-humus complexes and formation of allophane associations are mutually competitive. This is known as the '*binary composition'* of Andosols. It seems that allophane (and imogolite) is stable under mildly acid to neutral conditions (pH>5) whereas Al-humus complexes prevail in more acid environments. If there is still (excess) aluminium available

[2] *ferrihydrite* represents the short-range-order hydrous iron oxides previously termed 'amorphous ferric oxide' or 'iron oxide gel'. Neither its structure nor its composition has yet been established beyond doubt; a good approximation is probably: $Fe_2O_3.2FeOOH.\ 2.6H_2O$. Ferrihydrite is the dominant iron oxide mineral of most volcanic soils and some of the properties ascribed to allophane may in part be caused by ferrihydrite. Recent evidence suggests that much, if not all, organically bound iron (as extracted by pyrophosphate) is ferrihydrite-Fe.

[3] *imogolite* is a paracrystalline aluminosilicate consisting of smooth and curved threads with diameters varying from 10 to 30 nm and several thousands of nm in length. The threads consist of finer tube units of 2 nm outer diameter; their outer wall consists of a gibbsite (Al) sheet and the inner wall of a silica sheet.

under such acid conditions, this may combine with silicon to form 2:1 and 2:1:1 type phyllosilicate clay minerals (e.g. chlorite) that are often found in association with Al-humus complexes. The stability conferred on the organic matter by aluminium is no less in the presence of allophane. This suggests that the activity of aluminium in allophane is high enough to interact with organic molecules and prevent bio-degradation and leaching.

The competition between humus and silica for Al is influenced by environmental factors:

1. The '*Al-humus complex + opaline silica + phyllosilicate clay*' association is most pronounced in acidic types of volcanic ash that are subject to strong leaching. In practice, there is a continuous range in the binary composition of Andosols, from a pure Al humus complexes association ('non-allophanic') to an allophane/imogolite association ('allophanic'), in which the extremes are rare. This variation may occur within one profile or between profiles.
2. Following the *very* early stage of Andosol formation, (near-)complete inactivation of aluminium by organic matter may constrain the formation of allophane under humid temperate conditions. Aluminium will become available for mineral formation only after the rate of humus accumulation has levelled off. This explains why B-horizons in Andosols are usually much richer in allophane and imogolite than A-horizons: weathering of primary minerals proceeds but the supply of organic matter is limited so that little aluminium is tied up in Al-humus complexes.

The total pore fraction of the soil material increases greatly in the course of weathering, typically from some 50 percent to more than 75 percent (by volume). This is caused by leaching losses and stabilisation of the residual material by organic matter and weathering products (silica, allophane, imogolite, ferrihydrite).

The genesis of Andosols is further complicated if there is repeated deposition of fresh ash. Thin ash layers may just rejuvenate the surface soil material but thicker layers bury the soil. A new profile will then develop in the fresh ash layer while soil formation in the buried A-horizon takes a different course in response to the suddenly decreased organic matter supply and the different composition of the soil moisture.

The clay assemblage of Andosols changes over time, particularly that of the subsoil, as allophane and imogolite are transformed to halloysite, kaolinite or gibbsite (depending on the silica concentration of the soil solution). Aluminium from the Al-humus complexes will gradually become available and ferrihydrite will eventually turn into goethite. All these processes are strongly influenced by such factors as the rate of rejuvenation, the depth and composition of the overburden, the composition of the remaining material and the moisture regime. Eventually, an Andosol may grade into a 'normal' soil, e.g. a podzolized soil, or a soil with ferric properties, or with clay illuviation.

Characteristics of Andosols

Morphological characteristics

The 'typical' Andosol has an AC or ABC profile with a dark Ah-horizon, 20 to 50 cm thick (thinner or thicker occurs) on top of a brown B- or C-horizon. Topsoil and subsoil colours are distinctly different; colours are generally darker in humid, cool regions than in tropical climates.

The average organic matter content of the surface horizon is about 8 percent but the darkest profiles may contain as much as 30 percent organic matter. The surface horizon is very porous, very friable, and has a crumb or granular structure. In some Andosols the surface soil material is smeary and feels greasy or unctuous; it may become almost liquid when rubbed, presumably because of sol-gel transformations under pressure ('*thixotropy*').

Hydrological characteristics

Most Andosols have excellent internal drainage because of their high porosity and their occurrence in predominantly high terrain positions. Gleyic soil properties develop where groundwater occurs at shallow depth; stagnic properties are particularly prominent in paddy fields on terraced volcanic slopes, e.g. on Java and Bali (Indonesia).

Mineralogical characteristics

Quantities of volcanic glass, ferromagnesian minerals (olivine, pyroxenes, amphiboles), feldspars and quartz in the silt and sand fractions of Andosol material differ between sites. Some of the mineral grains may have acquired a coating of volcanic glass when the temperature was still high. The mineral composition of the clay fraction of Andosols varies with such factors as 'genetic age' of the soil, composition of the parent material, pH, base status, moisture regime, thickness of overburden ash deposits, and content and composition of soil organic matter. The clay fraction of Andosols contains typical 'X-ray amorphous materials' such as allophane and imogolite, and/or humus complexes of Al and Fe together with opaline silica. Allophane/imogolite and Al-humus complexes may occur together even though the two groups have conflicting conditions of formation. Besides primary minerals, ferrihydrite, (disordered) halloysite and kaolinite, gibbsite and various 2:1 and 2:1:1 layer silicates and intergrades can be present.

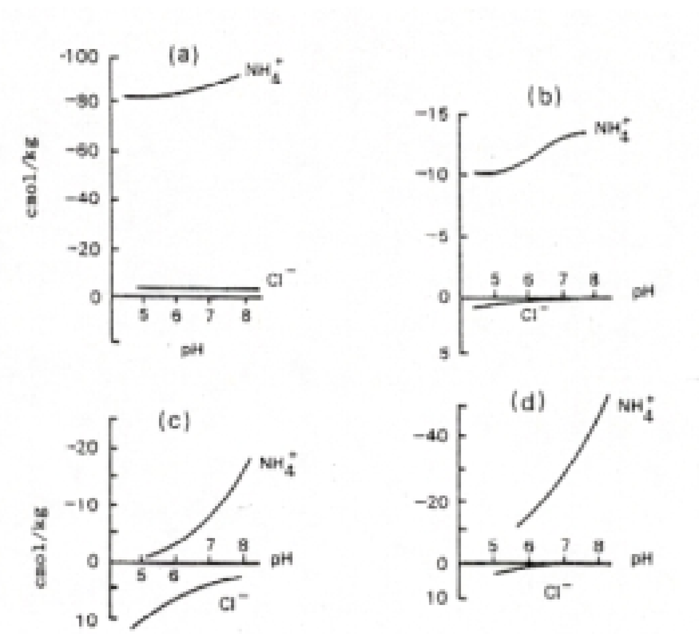
Physical characteristics

The good aggregate stability of Andosols and their high permeability to water make these soils (relatively) resistant to water erosion. Exceptions to this rule are highly hydrated types of Andosol that dried out strongly, e.g. after deforestation. The surface soil material of such Andosols crumbles to hard granules (*'high mountain granulation'*) that are easily removed with surface run-off water. The difficulty to disperse Andosol material gives problems in texture analysis; caution should be taken when interpreting such data.

The bulk density of Andosols is low, not just in the surface soil; it is typically less than 0.9 Mg/m^3 but values as low as 0.3 Mg/m^3 have been recorded in highly hydrated Andosols. The bulk density does not change much over a suction range of 1500 kPa (limited shrink and swell). Therefore, values determined on field-moist soil material can in practice be substituted for the bulk density at 'field capacity', which is diagnostic for identifying an '*andic*' horizon.

The moisture content at 1500 kPa suction ('permanent wilting point') is high in most Andosols; the quantity of 'available water' is generally greater than in other mineral soils. Excessive air-drying of Andosol material will irreversibly deteriorate water holding properties, ion exchange capacity, soil volume, and ultimately the cohesion of soil particles. In the extreme case these fall apart to a fine dust that is very susceptible to wind erosion.

Figure 2
NH_4^+ and Cl^- retention curves measured in 0.01 *M* NH_4Cl (0.1 *M* NH_4Cl for montmorillonite). (a) montmorillonite; (b) halloysite; (c) allophane 905 (Al:Si=2:1, containing some imogolite); (d) allophane PA (Al:Si=1:1). Wada & Okamura, 1977



Chemical characteristics

Andosols have highly variable exchange properties: the charge is strongly dependent on pH and electrolyte concentration. This is also the case with some other soils, e.g. Ferralsols, but the negative charge of Andosols can reach much higher values because of the high contents of soil organic matter and allophane.

Figure 2 shows, for some Andosol components, the variation in charge as a function of pH (the clay minerals halloysite and montmorillonite, having a dominantly permanent charge, are included for comparison).

With charge properties variable, base saturation values are also variable. Base saturation values are generally low because of strong leaching, except in some very young Andosols and in Andosols in dry regions.

The strong chemical reactivity of Andosols has long been attributed to X-ray amorphous compounds. It is more appropriate, however, to ascribe this Andosol characteristic to the presence of *'active aluminium*' which may occur in various forms:

1. in *short-range-order or paracrystalline aluminosilicates* such as allophane and imogolite.
2. as *interlayer Al-ions* in 2:1 and 2:1:1 layer silicates.
3. in *Al-humus complexes*, and
4. as *exchangeable Al-ions* on layer silicates.

The role of active iron may not be ignored but is generally considered of less importance than that of active aluminium.

Management and use of Andosols

Andosols have a high potential for agricultural production but many are not used to their capacity. By and large, Andosols are fertile soils, particularly Andosols in intermediate or basic volcanic ash and not exposed to excessive leaching. The strong phosphate fixation of Andosols is a problem. Ameliorative measures to reduce this effect (caused by active Al) include application of lime, silica, organic material and 'phosphate' fertilizer.

Andosols are easy to till and have good rootability and water storage properties. Strongly hydrated Andosols may pose problems on account of their low bearing capacity and their stickiness.

Andosols in the tropics are planted to a wide variety of crops including sugarcane, tobacco, sweet potato (tolerant of low phosphate levels), tea, vegetables, wheat and orchard crops. Andosols on steep slopes are perhaps best kept under forest. Paddy rice cultivation is a major landuse on Andosols in lowlands with shallow groundwater. Elsewhere, continued paddy rice production has resulted in formation of a dense hardpan over accumulation layers of iron and manganese oxides; these hardpans reduce percolation losses of (irrigation) water.

Major landforms in landscapes with sands

Parent material can decisively influence soil formation: soils in (almost) pure quartz sands are normally 'poor'. Extensive regions with such quartz-rich sands exist on earth. By and large, these can be divided into three broad categories:

1. *Residual sands* are the result of prolonged weathering of quartz-rich rocks such as granite, sandstone and quartzite. Chemical weathering is particularly active in wet and hot tropical regions where it leads to formation of chemically extremely poor substrates.
2. *Aeolian sands* are deposited by wind action, either in dunes or in extensive sheets (*'cover sand areas'*). Wind action is particularly effective in hot and dry regions such as deserts but sand dunes are also common in (sub)humid regions with sparse vegetation, notably in overgrazed areas and along beaches and fluvial 'braid plains'. The (weathering) history of the parent materials in the source area determines whether the sands are rich in quartz and/or carbonates.
3. *Alluvial sands* are transported by water. In general, these sands are less well-sorted and also less weathered - and therefore 'richer' - than aeolian sands. An exception are so called 'recycled' fluvial sands deposited by rivers that cut through thoroughly weathered rocks, predominantly in tropical regions (such as several tributaries of the Amazon River). Typical landforms in regions with fluvial sands will be discussed in more detail in the chapter on lowland regions; areas with alluvial sands are less extensive than residual and aeolian sands.

Residual sands

Extensive, horizontal sandstone plateaux occur in tropical shield areas. Well-known examples are the Precambrian Roraima sandstone formations on the Guiana Shield and the Voltaian sandstone formations in Western Africa. Major occurrences of consolidated sands are found in Northern Africa, in Guyana and Surinam, eastern Peru, northeastern Brazil and in Liberia (western Africa). These sandstone formations have a history of tropical weathering in common; they all have a deep weathering mantle of bleached, white sands that are very rich in quartz, poor in clay and excessively drained. Electrolyte contents differ by region:

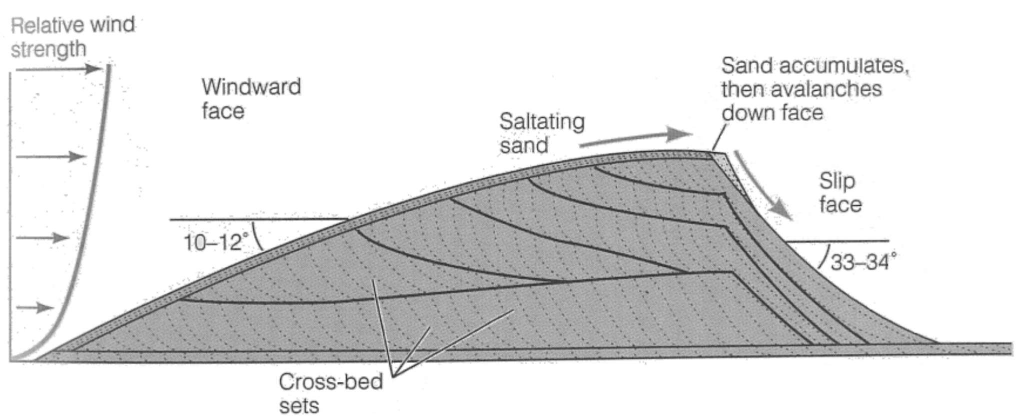
- In *arid and semi-arid areas* where evaporation exceeds precipitation, salts and carbonates may accumulate at or near the surface of the soil.
- In *humid areas* with white sands, leaching is the predominant process. Rivers have typically black, acid water of pH 4.0 or less (e.g. Rio Negro) indicating that organic compounds are leached from the sands. The sand grains lose any coating and become increasingly white (the colour of quartz). Eventually a thick albic E-horizon is formed, in places over a dark illuviation horizon at several metres depth. The influence of leaching can extend so deep into the saprolite that the albic horizon is to be regarded as parent material for subsequently forming 'new' soils: Arenosols.

Aeolian sands

Sandy parent materials are also abundant in areas where sand accumulates after selective transportation of weathering material by wind or water. Aeolian (wind-borne) sands will be discussed in this paragraph.

During transport, selection of particles (sorting and winnowing) occurs; the momentary wind speed and the size, shape and density of minerals determine how far a particular grain will be transported. Fine gravel travels by creep and sand-sized particles by saltation. Silt-sized particles can be carried over great distances (Saharan 'dust' settles regularly in central Europe and, in the past, loess formations have formed extensive blankets far from the source areas). Fine, plate-shaped clay minerals and micas are blown out and travel even farther (which explains why wind-borne sediments are normally poor in micas). This sorting of grains results in deposits that consist of pure sand with a uniform particle size. Many aeolian sand deposits show characteristic large-scale cross bedding, indicative of sand deposition on the slip faces of dunes. See Figure 1.

Figure 1
Schematic dune structure



'Fixed dunes' are formed when transported sand settles in the lee of an obstacle such as a brush or a piece of rock. The obstacle thus grows in size and more sand settles: the dune grows. The transport capacity of the wind decreases as it drives the sand grains to the top of the dune, causing an increasing part of the transported sand to settle before reaching the dune crest. This steepens the angle of the slope, particularly near the crest. Once the slope angle exceeds the angle of rest of the deposited sand (typically 34^o for dry sand), shearing sets in along a slightly less steep plane. Thus, a slip face is formed on the leeward side of the dune. Vegetation growing on (in particular) the lower part of dunes may eventually keep most of the sand in place. Dunes along coasts are often fixed by vegetation (natural or planted by man); *'parabolic dunes'* may develop by landward migration of beach sand.

'Free dunes' have no fixed position, but migrate downwind by erosion on the gently inclined windward side and deposition on the leeward side (slip face) in the same way as described for fixed dunes. The smallest free dunes are common wind ripples that measure only a few centimetres in height. Large dunes are found in extensive dune areas in deserts, in sand seas known as '*ergs*'.

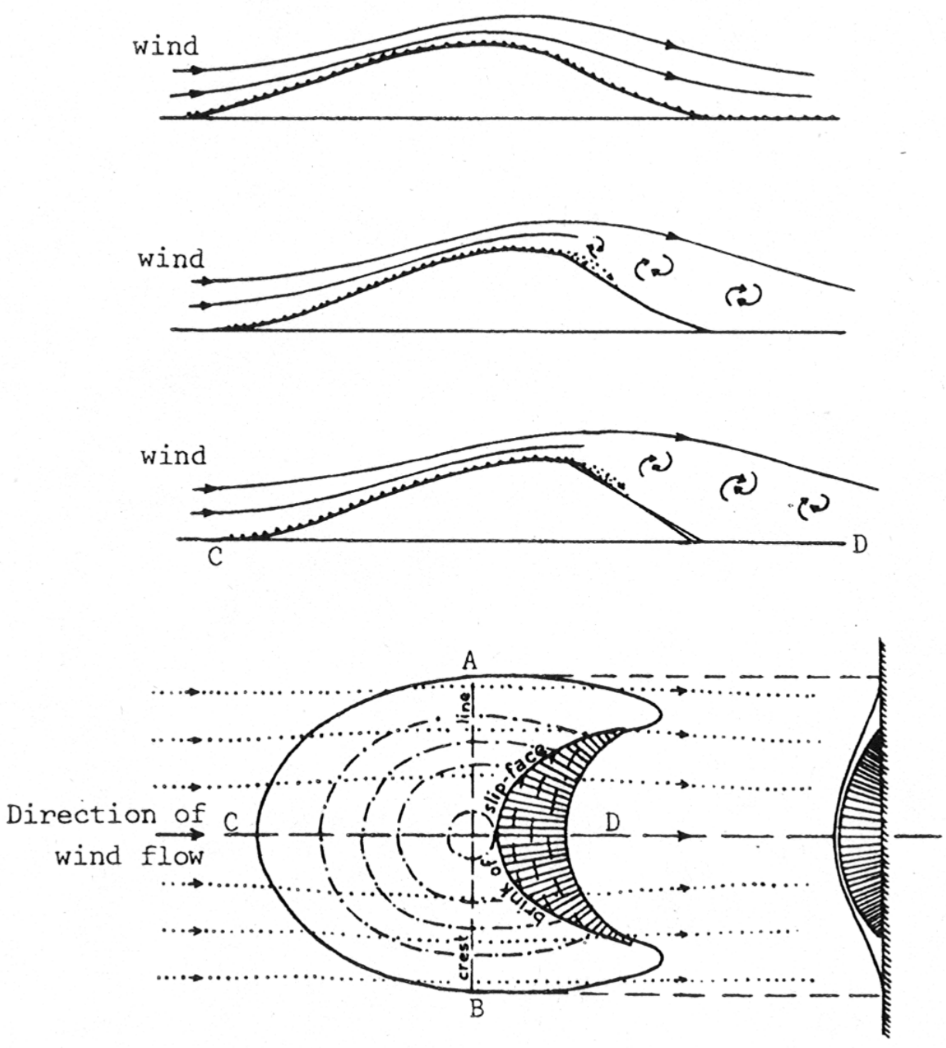
Coastal dunes occur along beaches or sand-flats that form part of a non-erosional sandy or deltaic coast. The source areas of the sand will eventually lose all sand, silt and clay particles; some become wet (groundwater) depressions whereas others acquire a rocky or boulder-strewn surface known as a *'desert pavement'*.

Two main types of free dunes are distinguished, viz. *'crescentic'* dunes and *'linear'* dunes.

- *Crescentic dunes* are typically wider than long. They assume a crescent shape (*'barchan dunes'*) where winds are predominantly uni-directional. The rate of advancement of the sand is roughly inversely proportional to the height of the crest. This causes the flanks of a shifting dune to advance more rapidly than the central part until the flanks become sheltered by the main mass of the dune. Coalescing barchans produce *'transverse dunes'*. Figure 2 vizualises barchan-dune formation.
- *Linear* or *longitudinal dunes* (also known as *'seifs'*) are straight or slightly sinuous, symmetrical sand ridges that are typically much longer than wide. The surface between individual ridges may be covered either with sand or have a gravel or boulder pavement. More or less stable *'star dunes*' (also known as '*ghourds*') occur in regions with varying wind directions. A star dune has one high central part, with several arms radiating outwards. Star dunes tend to grow in height rather than move; they are a common feature in the Sahara *'erg'*.

The area of actual 'erg' and dune formation is delimited by the 150 mm/yr isohyet. This precipitation boundary appears to have shifted strongly in the recent past. Between 20,000 and 13,000 yr. BP, the southern limit of active dune formation in the Sahara desert was 800 km south of its present position and most of the now sparsely vegetated Sahelian zone was an area of active dune formation at that time. These dunes, mostly of the longitudinal type, are now fixed by vegetation, but their aeolian parentage is still obvious from their well-sorted material. A similar story can be told for the Kalahari sands. Overgrazing in recent times has reactivated aeolian transport in many regions with sands.

Figure 2
The formation of barchan dunes. Source: Bagnold, 1965

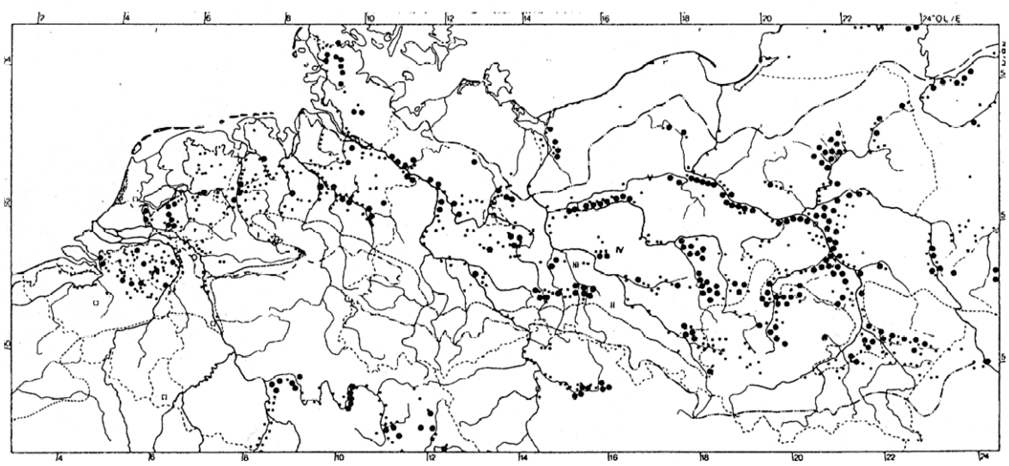


Cover sands

The cover sands (sheet deposits and associated parabolic dunes) of the temperate climate zone were mainly formed under *'periglacial'* (= polar desert) conditions during the arid interval between 20,000 and 13,000 years BP. River dunes in north-west Europe have for the greater part formed by local deflation of sand from the plains of braided rivers during the cold Younger Dryas period (10,500 to 10,150 years BP). Forests, notably pine forests, re-established on most of these sands, but overgrazing by sheep in medieval times sparked renewed (wind) erosion. Young *'anthropogenic'* dunes with Arenosols are common in many parts of west and central Europe. See Figure 3.

Similar periglacial dune fields with Arenosols are found in (more continental) parts of North America (Canada) and Russia.

Figure 2
Cover sands in Europe. Source: Koster, 1978



ARENOSOLS (AR)

The Reference Soil Group of the Arenosols consists of sandy soils, both soils developed in residual sands, *in situ* after weathering of old, usually quartz-rich soil material or rock, and soils developed in recently deposited sands as occur in deserts and beach lands. Many Arenosols correlate with Psamments and Psammaquents of the USDA Soil Taxonomy. Deep sandy soils with an argic or a spodic horizon within 200 cm from the surface are 'Grossarenic' subgroups within the Alfisol, Ultisol and Spodosol orders. In the French classification system (CPCS, 1967), Arenosols correlate with taxa within the "Classe des sols minéraux bruts" and the "Classe des sols peu évolués". Other international soil names to indicate Arenosols are 'siliceous, earthy and calcareous sands' and various 'podsolic soils' (Australia), 'red and yellow sands' (Brazil) and the Arenosols of the FAO Soil Map of the World.

Definition of Arenosols[#]

Soils, having
1. a texture, which is loamy sand or coarser *either* to a depth of at least 100 cm from the soil surface, *or* to a *plinthic*[@], *petroplinthic*[@] or *salic*[@] horizon between 50 and 100 cm from the soil surface; and
2. less than 35 percent (by volume) of rock fragments or other coarse fragments within 100 cm from the soil surface; and
3. no diagnostic horizons other than an *ochric*[@], *yermic*[@] or *albic*[@] horizon, or a *plinthic*[@], *petroplinthic*[@] or *salic*[@] horizon below 50 cm from the soil surface.

Common soil units:
Gelic*, Hyposalic*, Gleyic*, Hyperalbic*, Plinthic*, Hypoferralic*, Hypoluvic*, Tephric*, Gypsiric*, Calcaric*, Albic*, Lamellic*, Fragic*, Yermic*, Aridic*, Protic*, Dystric*, Eutric*, Rubic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Arenosols

Connotation: sandy soils; from L. *arena*, sand.

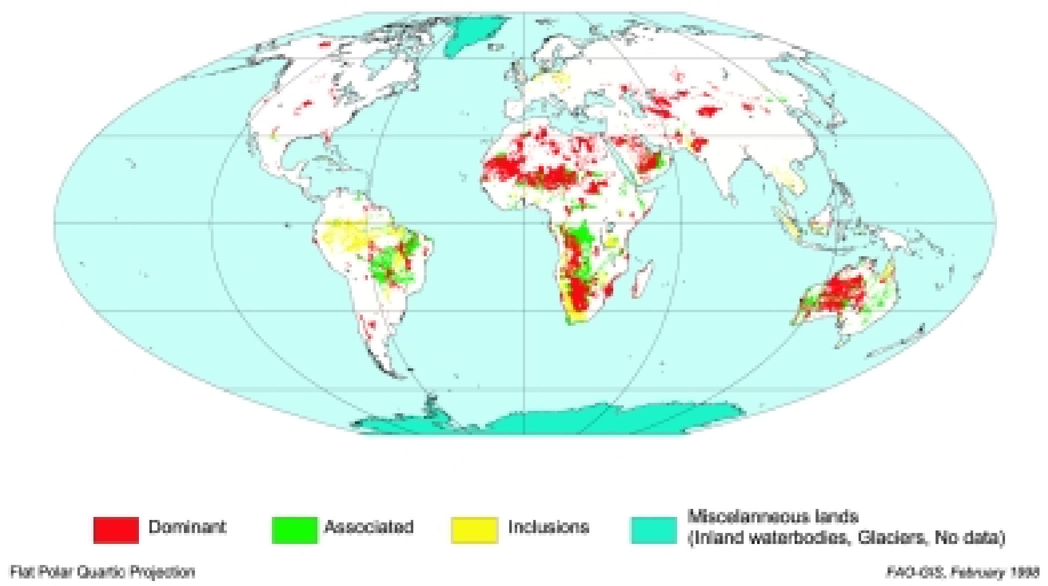
Parent material: unconsolidated, in places calcareous, translocated sand; relatively small areas of Arenosols occur on residual sandstone or siliceous rock weathering.

Environment: from arid to (per)humid and from extremely cold to extremely hot; landforms vary from recent dunes, beach ridges and sandy plains under scattered (mostly grassy) vegetation, to very old plateaus under light forest.

Profile development: A(E)C profiles. In the dry zone, an *ochric* surface horizon is the only diagnostic horizon. Arenosols in the perhumid tropics tend to develop thick *albic* eluviation horizons; most Arenosols of the humid temperate zone show signs of alteration or transport of humus, iron or clay, but too weak to be diagnostic.

Use: most Arenosols in the dry zone are used for little more than extensive grazing but they could be used for arable cropping if irrigated. Arenosols in temperate regions are used for mixed arable cropping and grazing; supplemental (sprinkler) irrigation is needed during dry spells. Arenosols in the perhumid tropics are chemically exhausted and highly sensitive to erosion. They are best left untouched.

Figure 1
Arenosols world-wide



Regional distribution of Arenosols

Arenosols are among the most extensive soils in the world, covering about 900 million ha or 7 percent of the land surface. If shifting sands and active dunes ('non-soils') were included, the coverage would be about 10 percent. Vast expanses of deep aeolian sands are found on the central African plateau between the equator and 30º southern latitude. These 'Kalahari Sands' form the largest body of sands on earth. Other areas of Arenosols occur in the Sahelian region of Africa, various parts of the Sahara desert, central and western Australia, the Middle East and China. Sandy coastal plains and coastal dune areas are of smaller geographic extent.

Although most Arenosols occur in arid and semi-arid regions, they are typical *azonal* soils; they are found in the widest possible range of climates, from very arid to perhumid and from cold to hot. Arenosols are widespread in aeolian landscapes but occur also in marine, littoral and lacustrine sands and in coarse-grained weathering mantles of siliceous rocks, mainly sandstone, quartzite and granite.

There is no limitation as to age or period in which soil formation took place. Arenosols occur on very old surfaces as well as in very recent landforms, and may be associated with almost any type of vegetation. Figure 1 presents a sketch map of the main occurrences of Arenosols world-wide.

Associations with other Reference Soil Groups

Arenosols have linkages with almost any other Reference Soil Group. With some groups the surmised linkage is rather theoretical and probably rare, with others the linkage is obvious and well documented. A broad division can be made between *Arenic* units of other Reference Soil Groups and soil units of Arenosols.

Arenic units

The qualifier *'Arenic'*, indicating a texture of loamy sand or coarser throughout the upper 50 cm of the soil, is recognised for all Reference Soil Groups except Histosols, Cryosols, Leptosols, Vertisols, Solonchaks, Podzols, Plinthosols, Solonetz, Chernozems, Kastanozems, Phaeozems, Gypsisols, Calcisols, Nitisols and Cambisols. It is possible that Arenic units exist within these Reference Soil Groups but that they have not (yet) been sufficiently documented. If so, they are probably rare. Because of "opposed" textural requirements no linkage exists e.g. with Vertisols.

Most Podzols have a sandy texture and therefore it would not make sense to use the qualifier 'Arenic'; Leptosols are excluded because of the shallowness requirement.

Lower level units of Arenosols

Lower level units of the Arenosol group are linked with Cryosols (Gelic Arenosols), Solonchaks (Hyposalic Arenosols), Gleysols (Gleyic Arenosols), Andosols (Tephric Arenosols), Podzols (Albic or Hyperalbic Arenosols), Plinthosols (Plinthic Arenosols), Ferralsols (Hypoferralic Arenosols), Gypsisols (Gypsiric Arenosols), Durisols (Hypoduric Arenosols) and Calcisols (Calcaric Arenosols).

Special relationships exist with soils having thick sandy layers over an argic, ferralic or spodic subsurface horizon. In Alisols, Acrisols, Luvisols and Lixisols loamy sand or coarser textures are permitted if the argic horizon (by definition sandy loam or finer) occurs within 200 cm of the surface. In addition the qualifier "Hypoluvic" links Arenosols to Luvisols.

Soils with a ferralic horizon starting within 170 cm of the surface qualify as Ferralsols, irrespective of the texture of the overlying horizons. Similarly, soils with a spodic horizon starting within 200 cm of the surface are Podzols.

Planosols and Albeluvisols may have sandy textures in the upper part of the solum, but the presence of an *abrupt textural change* or of an *argic* horizon within 100 cm excludes qualifiers linking these soils to Arenosols.

Genesis of Arenosols

The development of Arenosols of the dry zone is distinctly different from that of Arenosols in the wet tropics. Arenosols in the dry zone show minimal profile development because soil forming processes are at a standstill during long periods of drought and/or because the parent material is of young age. Arenosols in the wet tropics formed in young sandy deposits or, the other extreme, constitute the thick albic E-horizon of a Giant Podzol and represent the ultimate in soil formation.

Arenosols of the Dry Zone

Most Arenosols in the dry zone are associated with areas of (shifting) sand dunes. Evidently, soil formation in such dune sand is minimal until the dune is colonized by vegetation and held in place. Then, some humus can accumulate in the surface soil and a shallow, ochric surface horizon can develop; 'Aridic' Arenosols contain less than 0.2 percent organic carbon and show evidence of aeolian activity. The sand grains of Arenosols in the dry zone may acquire a coating of (brownish) clay and/or carbonates or gypsum. In places, desert sand is deep red by coatings of goethite ('*ferrugination*', a relic feature according to some). Where the parent material is gravelly, sand is blown out of the surface layer and the coarser constituents remain behind at the soil surface as a *'desert pavement'* of polished pebbles and stones. 'Yermic' Arenosols may be found in such situations. Depending on parent material and topographical situation, 'Gypsiric', 'Calcaric', 'Hyposalic' and 'Hypoduric' Arenosols, or combinations of these, occur as intergrades to Gypsisols, Calcisols, Solonchaks and Durisols. High permeability, low water storage capacity and low biological activity all promote decalcification of the surface layer(s) of Arenosols in the dry zone, even though the annual precipitation sum is extremely low.

Arenosols of the Temperate Zone

Arenosols in the Temperate Zone show signs of more advanced soil formation than Arenosols in arid regions. They occur predominantly in fluvio-glacial, alluvial, lacustrine, marine or aeolian quartzitic sands of very young to Tertiary age. In young fluvio-glacial or marine sandy deposits, pedogenesis would most likely proceed as follows: in geomorphologically stable conditions a plant cover establishes itself and calcareous sands are deeply decalcified. An ochric surface horizon forms, which contains humus of the *'moder'* type, consisting for the greater part of excrements. Soluble organic substances produced in the ochric surface horizon percolate downward while forming complexes with iron and aluminium (*'cheluviation'*, see under Podzols). At this stage the soils show signs of beginning '*podzolization*' with accumulation of Fe- and Al-humus complexes in thin lamellae. If the process continues until a true spodic subsurface horizon has formed, the soil has become a Podzol. In very poor sands (low in clay, silt and weatherable minerals), the incipient spodic horizon consists almost entirely of humus (Bh) whereas in richer materials it also contains amorphous, dispersible, humus-sequioxide complexes (Bhs). Human intervention can result in formation of an *anthric* horizon (e.g. 'plaggic horizon'). Once the thickness of the anthric horizon reaches 50 cm or more the soil becomes an Anthrosol, otherwise the qualifier 'Anthric' (or 'Plaggic') applies.

Lamellae may be of different origin and composition. Lamellae in geomorphologically unstable aeolian or fluvio-glacial deposits are mere markers of short periods of stability and vegetative cover alternating with periods of wind erosion and deposition. In more stable situations, lamellae are formed by vertical transport, after decalcification, of fine components over short distances. Humus and/or humus-iron complexes precipitate as the ratio of sequioxides to organic carbon increases in the course of cheluviation or upon saturation after evaporation at the depth of water penetration. Clay lamellae commonly follow visible stratification and are correlated with differences in pore size. Pores slightly larger than those in the next deeper layer cause water to 'hang' (unsaturated flow). If this water is withdrawn by plants or as vapour, any suspended clay is left behind and the difference in size of pores is accentuated. Thus, once the process has begun, clay continues to accumulate in the same place. The process may take place at several depths. Once the combined thickness of clay lamellae exceeds 15 cm within 100 cm from the surface, the qualifier '*lamellic*' applies. The effect of lamellae on the water-holding capacity of the soil can be significant because water hangs on each lamella.

Biological homogenization may counteract the transport of metal-humus complexes or suspended clay in loamy sands that are relatively rich and deep. In this case homogeneous, brown or reddish profiles develop; many with an orange-red colour under the ochric surface horizon, indicative of thin (<10^{-5} m) iron coatings on the sand grains.

Arenosols of the Humid Tropics

Arenosols in the humid tropics are either young soils in coarsely textured alluvial, lacustrine or aeolian deposits, or they are very old soils in residual acid rock weathering that lost all primary minerals other than (coarse grained) quartz in the course of an impressive pedogenetic history.

The *young* Arenosols of beach ridges and coastal plains, are *azonal* soils; they merely have a thin brown ochric surface horizon over a deep subsoil that may have gleyic properties and/or show signs of beginning horizon differentiation that are taxonomically insignificant.

The *old* (Albic) Arenosols constitute the deep, bleached surface soils of Giant Podzols whose albic horizon extends downward to a depth below 100 cm from the surface ('Hyperalbic'). If the underlying spodic horizon starts within 200 cm, the soil is classified as a Podzol but where the spodic horizon starts deeper (beyond the taxonomic control section) the soil is back among the Arenosols. These Arenosols are *zonal* soils; they result from intense and prolonged dissociation of weatherable minerals and translocation of the weathering products.

Characteristics of Arenosols

Morphological characteristics

Arenosols in the arid zone have a beginning A-horizon with weak single grain or crumb structure over a massive C-horizon. Arenosols in the temperate zone have better developed but still ochric surface horizons over a substratum that may have thin iron coatings throughout, or contain lamellae of illuviated humus, clay or iron compounds that are too thin, too few or contain too little humus to qualify as a diagnostic horizon. Young tropical Arenosols are morphologically not very different from those in temperate regions. Old tropical Arenosols under forest on residual quartzitic rock weathering or sandy deposits have a dark brown O-horizon over a shallow greyish brown mineral surface horizon that tops a deep, grey to white, coarse sandy eluvial horizon (e.g. *"Giant Podzols"*). A shallow mini-Podzol may form in the A-horizon; it remains intact because biological activity is virtually absent.

Hydrological characteristics

Coarsely textured soils hold a much greater proportion of their 'available' water at low suctions than finer soils. Since most of the pores are relatively large, much of the retained moisture is lost at a soil suction of only 100 kPa. Depending on the grain size distribution and organic matter content, the 'Available Water (storage) Capacity' (AWC) may be as low as 3 to 4 percent or as high as 15 to 17 percent.

Arenosols are permeable to water; saturated hydraulic conductivity varies with the packing density of the sand and can assume any value between 300 and 30,000 cm/day. Infiltration of water in sandy soils varies between 2.5 and 25 cm/hour and may be 250 times faster than in clay soils (0.01 – 0.1 cm/hr). *Note that* under unsaturated flow conditions water moves more slowly in sandy soils than in clayey soils on account of their lower moisture content and lower unsaturated hydraulic conductivity. Understanding these relations is important for proper irrigation and drainage practices.

Mineralogical characteristics

The principal minerals found in the sand and silt fractions of Arenosols are quartz and feldspars and, to a lesser extent, micas, ferromagnesian minerals (pyroxenes, amphiboles, olivines) and 'heavy' minerals (zircon, garnet, tourmaline, ilmenite, magnetite, rutile, etc). The nature of the clay fraction is conditioned by weathering conditions and parent rock. Aggregates of certain clay minerals (e.g. vermiculite, chlorite and kaolin) may be large enough to belong to the sand or silt fraction of the soil.

Physical characteristics

Arenosols have relatively high bulk density values that are typically between 1.5 and 1.7 kg dm^{-3}; somewhat lower or higher values are not uncommon. With the specific gravity of quartz close to 2.65 g dm^{-3}, the calculated total porosity of Arenosols amounts to 36 to 46 volume-percent, less than that of most finely textured soils. Arenosols have a high proportion of large pores that account for their good aeration, rapid drainage and low moisture holding capacity.

Most sands and loamy sands are non-coherent, 'single grain' materials, especially in the absence of organic matter or other cementing agents. Arenosols are predominantly 'structureless'; they are 'non-sticky' and 'non-plastic' when wet and 'loose' when dry. A cemented or indurated layer may occur at some depth.

Static loads produce very little compaction of Arenosols but vibration does; fine sand in a loose state and saturated with water is a very unstable material, especially in embankments.

Chemical characteristics

- Most Arenosols in *humid temperate* or *tropical* regions are deeply leached and decalcified soils with a low capacity to store bases. Their A-horizons are shallow and/or contain little or poorly decomposed organic matter. The natural (forest) vegetation survives on cycling nutrients and roots almost exclusively in the O-horizon and in a shallow A-horizon.
- Rooting is deeper and nutrient cycling less vital to the vegetation in Arenosols in *temperate* regions, particularly those in loamy sands. The organic carbon content of well-drained Arenosols is normally less than 1 percent; 2 to 3 percent may be present in the upper 10 to 20 cm of soil. The CEC is typically low except in the upper 10 to 20 cm layer. The *effective* CEC (ECEC) is normally less than 4 cmol(+) kg^{-1} soil but may reach somewhat higher values in the topsoil.
- Arenosols in *dry* regions are normally rich in bases. Moderate leaching and shallow decalcification may still occur. The organic carbon contents of most surface horizons are normally less than 0.5 percent (less than 0.2 percent in the subsoil). CEC and ECEC values are not as low as one might have expected in view of the low organic carbon content; this is explained by a higher proportion of smectitic (and/or vermiculitic and chloritic) clay minerals than are found in Arenosols in humid areas.

Management/use of Arenosols

Arenosols occur in vastly different environments and possibilities to use them for agriculture vary accordingly. All Arenosols have a coarse texture, accountable for the generally high permeability and low water and nutrient storage capacity. Arenosols are further marked by ease of cultivation, rooting and harvesting of root and tuber crops.

- Arenosols in *arid lands*, where the annual rainfall sum is less than 300 mm, are predominantly used for extensive (nomadic) grazing. Dry farming is possible where the annual rainfall sum exceeds 300 mm. Low coherence, low nutrient storage capacity and high sensitivity to erosion are serious limitations of Arenosols in the dry zone. Good yields of small grains, melons, pulses and fodder crops have been realized on irrigated Arenosols but high percolation losses may make surface irrigation impracticable. Drip or trickle irrigation, combined with careful dosage of fertilizers, may remedy the situation. Many areas with Arenosols in the Sahelian zone (300 to 600 mm rainfall per annum) are transitional to the Sahara desert; their soils are covered with sparse vegetation. Uncontrolled grazing and clearing for cultivation without appropriate soil conservation measures can easily make these soils unstable and revert the land to shifting dune areas.
- Arenosols in the *(sub)humid temperate zone* have similar limitations as the Arenosols of the dry zone albeit that drought is a less serious constraint. In some instances, e.g. in horticulture, the low water storage of Arenosols is considered advantageous because the soils warm up early in the season. In (much more common) mixed farming systems with cereals, fodder crops and grassland, supplemental sprinkler irrigation is applied to prevent drought stress during dry spells. A large part of the Arenosols of the temperate zone are under forest, either production forest or 'natural' stands in carefully managed 'nature' reserves.

Arenosols in the *humid tropics* are best left under their natural vegetation, particularly so the deeply weathered Albic Arenosols. As nutrient elements are all concentrated in the biomass and in the top 20 cm of the soil, removal of the vegetation inevitably results in infertile badlands without ecological or economic value. Under forest, the land can still produce some timber (e.g. *Agathis spp.*) and wood for the pulp and paper industry. Permanent cultivation of annual crops would require management inputs that are usually not economically justifiable. In places, Arenosols have been planted to perennial crops such as rubber and pepper; coastal sands are widely planted to estate crops such as coconut, cashew, casuarina and pine, especially where good quality groundwater is within reach of the root system. Root and tuber crops benefit from the ease of harvesting, notably cassava, with its tolerance of low nutrient levels. Groundnut and bambara groundnut can be found on the better soils.

Major landforms in landscapes with smectites

Soil materials whose properties are dominated by an abundance of expanding 2:1 lattice clays are associated with specific soils that show signs of seasonal swelling (wet) and shrinking (dry). Such soils can occur in many landscape elements. They are particularly extensive in:

1. (Former) *sedimentary lowlands*,
2. *Denudation plains* on Ca-, Mg- and Na-rich parent rock, and
3. Erosive *uplands with limestone, claystone, marls or shale*.

Landforms in (former) sedimentary lowlands

Sedimentary lowlands with expanding *'smectitic'* clays cover large areas, e.g. along the southern border of the Sahara desert where lakes and floodplains were abundant between 12,000 and 8,000 years BP, when the climate was more humid than at present. The Saharan lakes (notably Lake Chad), the inland delta of the river Niger and the alluvial plains of the Nile were much larger then than at present. The level of Lake Chad was until 40 metres higher than today and the lake had the size of the present Caspian Sea. Most rivers in the Sahelian zone, even those that are intermittent *'wadis'* in our time, flowed continuously in meandering channels and deposited finely textured sediments.

Much of what is known about the former expansion of the Saharan lakes was revealed by palynological studies of diatoms and pollen contained in lacustrine sediments. It is believed that large parts of the present Sahara desert were once colonised by savannah vegetation. Rock drawings in the area suggest that ostriches, rhinoceroses, crocodiles and giraffes once lived there. The (then) more humid climate is attributed to southward penetration of polar air masses when subtropical high-pressure cells were weaker than at present. Later in the Holocene, notably after 5000 years BP, the climate became drier again; lake levels dropped and rivers became intermittent. Under this regime of alternating dry and wet spells, Vertisols could form in the alluvial deposits.

In North America, large ice-dammed lakes (e.g. Lake Agassiz in central Canada and Lake Bonneville in Utah, USA) were formed during de-glaciation of the 'Laurentide' ice sheet (14,000 - 9000 years BP). Smectitic clays accumulated in the more central parts of these lakes. The North American landmass experienced alternating wetter and drier periods during the Holocene. Soils with *'vertic properties'* are found in low landscape positions in regions that are currently semi-arid.

Vertisols in marine clays can be found in coastal zones with active crustal uplift, e.g. on plateaux (coastal terraces) that once were lagoon areas. This is particularly common along the western (pacific) coast of Central America.

Landforms in denudation plains on base-rich parent rock

Denudation plains with smectitic clays occur in the same (semi-arid) climate zone but are restricted to areas where the parent rock is rich in Ca, Mg and Na. Most denudation plains are underlain by basic volcanic rock such as the flood basalts of the Deccan Traps in India, or by basic basement rocks, e.g. amphibolites and greenschists. Vertisol formation is especially plausible where shallow groundwater held ‘bases’ (Ca, Mg and Na) in solution and neo-formation of smectites could occur, e.g. in plains and on extensive, poorly drained plateaux.

Landforms in erosive uplands with limestone, claystone, marls or shale

Poorly consolidated clays, marl or shale have become exposed at the surface in many landscapes with actively incising rivers, usually in uplifting settings. In contrast with sedimentary lowlands and denudation plains, there is no direct relationship between current conditions and the environment in which the smectitic clays were deposited. The clays originate from a marine environment or were once incorporated in limestone or marl. Uplift and renewed denudation of the landscape brought the strata to the surface again. After limestone or marl became exposed to chemical weathering, the clastic residues were transported to lower positions in the landscape. Local hydrological conditions determine whether can Vertisols form or not. If the clay accumulates in wet depressions, Vertisols can form provided that there is a dry season that is long and dry enough for the clay to shrink and crack and develop vertic properties in a subsequent wet spell. If the clay is on well-drained slopes, its swell and shrink may induce mass wasting such as landslides and slumps.

VERTISOLS (VR)

Vertisols are churning heavy clay soils with a high proportion of swelling 2:1 lattice clays. These soils form deep wide cracks from the surface downward when they dry out, which happens in most years. The name Vertisols (from L. *vertere*, to turn) refers to the constant internal turnover of soil material. Some of the many local names became internationally known, e.g. 'black cotton soils' (USA), 'regur' (India), 'vlei soils' (South Africa), 'margalites (Indonesia), and 'gilgai' (Australia).

Definition of Vertisols[#]

Soils having
1. a *vertic*[@] horizon within 100 cm from the soil surface, and
2. after the upper 20 cm have been mixed, 30 percent or more clay in all horizons to a depth of 100 cm or more, or to a contrasting layer between 50 and 100 cm (e.g. a *lithic** or *paralithic** contact, *petrocalcic*[@], *petroduric*[@] or *petrogypsic*[@] horizons, or a sedimentary discontinuity), and
3. cracks[1], which open and close periodically.

Common soil units:
Thionic*, Salic*, Natric*, Gypsic*, Duric*, Calcic*, Alic*, Gypsiric*, Grumic*, Mazic*, Mesotrophic*, Hyposodic*, Eutric*, Pellic*, Chromic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifiers for naming soil units; see Annex 3 for full definition.

Summary description of Vertisols

Connotation: churning heavy clay soils; from L. *vertere*, to turn.

Parent material: sediments that contain a high proportion of smectitic clay, or products of rock weathering that have the characteristics of smectitic clay.

Environment: depressions and level to undulating areas, mainly in tropical, semi-arid to (sub)humid and Mediterranean climates with an alternation of distinct wet and dry seasons. The climax vegetation is savanna, natural grassland and/or woodland.

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[1] a crack is a separation between gross polyhedrons. If the surface soil is strongly self-mulching ('*grumic*'*), or if the soil is cultivated while cracks are open, the cracks may be filled with granular material from the surface but they remain 'open' in the sense that polyhedrons are separated. Vertisols develop cracks from the soil surface downward at some period in most years unless the soil is irrigated.

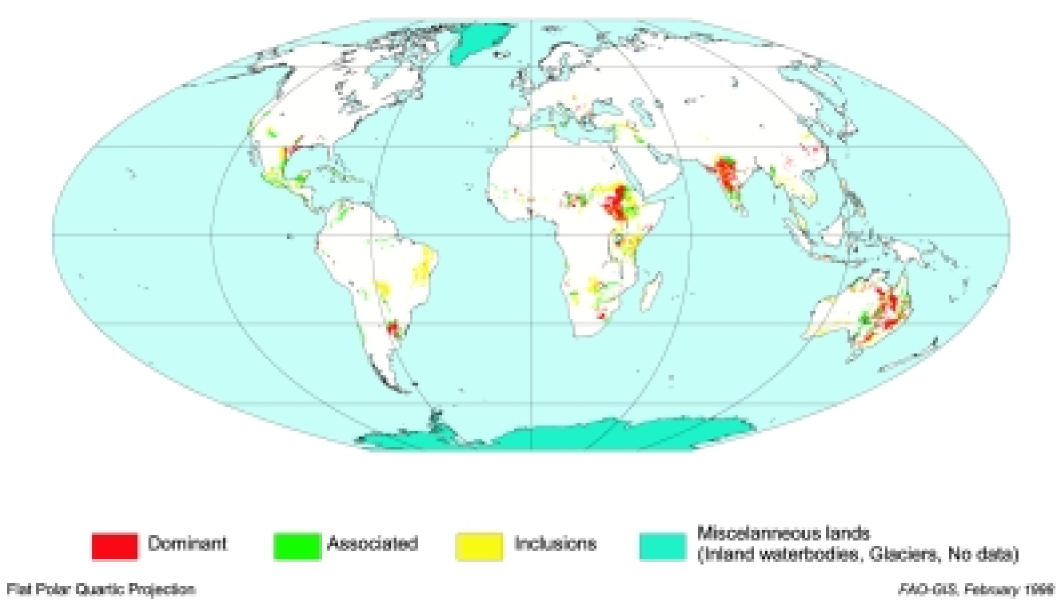
Profile development: A(B)C-profiles. Alternate swelling and shrinking of expanding clay results in deep cracks during the dry season, and formation of *'slickensides'* and wedge-shaped structural elements in the subsurface soil.

Use: Vertisols become very hard in the dry season and are sticky in the wet season. Tillage is difficult, except for a short period at the transition between the wet and dry seasons. Vertisols are productive soils if properly managed.

Regional distribution of Vertisols

Vertisols cover 335 million hectares world-wide. An estimated 150 million hectares is potential cropland. Vertisols in the tropics cover some 200 million hectares; a quarter of this is considered to be 'useful'. Most Vertisols occur in the semi-arid tropics, with an average annual rainfall sum between 500 and 1000 mm but Vertisols are also found in the wet tropics, e.g. in Trinidad where the annual rainfall sum amounts to 3000 mm. The largest Vertisol areas are on sediments that have a high content of smectitic clays or produce such clays upon post-depositional weathering (e.g. in the Sudan) and on extensive basalt plateaux (e.g. in India and Ethiopia). Vertisols are also prominent in Australia, southwestern USA (Texas), Uruguay, Paraguay and Argentina. Vertisols are typically found in lower landscape positions such as dry lake bottoms, river basins, lower river terraces and other lowlands that are periodically wet in their natural state. Depending on parent rock and environmental conditions, Vertisols occur only in bottomlands or also on contiguous lower foot slopes or, as residual soils, even on (gently) sloping hillsides. Figure 1 gives an overview of the world-wide occurrence of Vertisols.

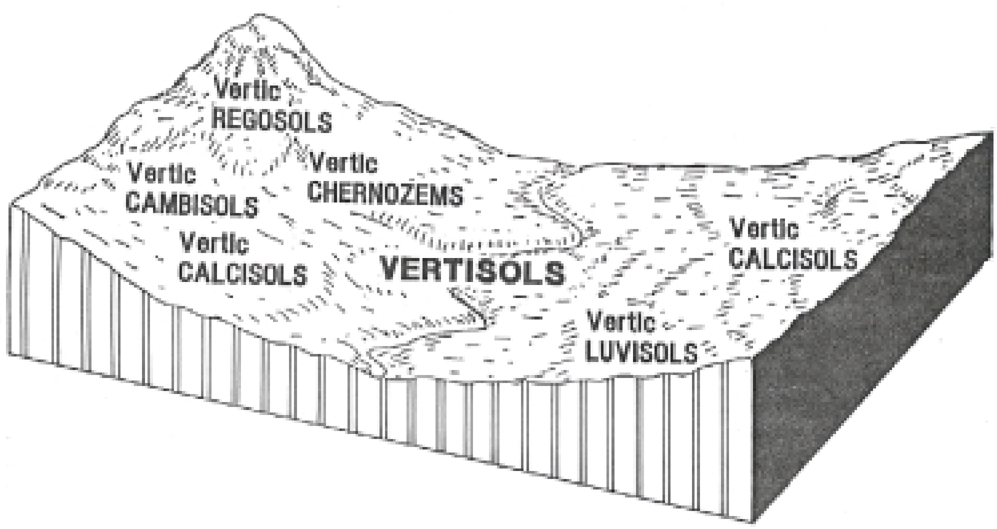
Figure 1
Vertisols world-wide



Associations with other Reference Soil Groups

Vertisols stand apart from other soils by having a *vertic* horizon, with high clay content, typical wedge-shaped or parallelepiped structural aggregates, and intersecting *'slickensides'*. They form deep, wide cracks upon drying. Other soils may show one or more of these properties, but not to the extent characteristic of Vertisols. Such soils form intergrades and extragrades to Vertisols and normally occur together with Vertisols. They may have cracks that are not sufficiently wide, or slickensides or wedge-shaped aggregates only, or a vertic horizon underlying a coarser textured surface layer, or they may be clayey with a beginning vertic horizon that has not yet become sufficiently deep. Most associated vertic intergrades (e.g. Vertic Calcisols, Luvisols, Cambisols) occur in higher landscape positions than Vertisols, e.g. on gently sloping or moderately steep plateaux, on mesas and on pediment surfaces. Figure 2 presents a Vertisol landscape with associated soils.

Figure 2
Vertisol landscape with associated soils



In the same topographic position, Vertisols on the arid side of the climatic spectrum grade into soils with accumulated soluble compounds (Calcisols, Gypsisols, Solonchaks), a consequence of the high evaporation surplus. On the humid side, intergrades to Vertisols have stronger accumulation of organic matter because of more luxuriant vegetation (e.g. Phaeozems and Chernozems). Toposequences with Nitisols and/or Luvisols (on slopes) and Vertisols/Planosols (in low-lying positions) are common in tropical and subtropical regions with basic rocks. Areas with sodium-rich parent materials may develop combinations of Vertisols and Solonetz, with the latter in a transitional position between upland soils (often Luvisols) and Vertisols. In river areas, depositional patterns play a role in the lateral linkages with other soils. Vertisols in backswamps are commonly associated with Solonetz and/or Planosols in more elevated positions, and with Fluvisols, Gleysols (and even Histosols) in central backswamp areas. Vertisols in marine deposition areas may occur alongside Solonchaks.

Genesis of Vertisols

Formation of smectite-rich parent material

The environmental conditions that lead to the formation of a *vertic* soil structure are also conducive to the formation of suitable parent materials.

1. Rainfall must be sufficient to enable weathering but not so high that leaching of bases occurs.
2. Dry periods must allow crystallization of clay minerals that form upon rock or sediment weathering.
3. Drainage must be impeded to the extent that leaching and loss of weathering products are curbed.
4. High temperatures, finally, promote weathering processes. Under such conditions smectite clays can be formed in the presence of silica and basic cations - especially Ca^{2+} and Mg^{2+} - if the soil-pH is above neutral.

The formation of Vertisol parent materials and Vertisol profiles becomes evident if one examines 'red-black' soil catenas[2], as abundant in Africa, on the Indian subcontinent and in Australia (Blokhuis, 1982). The typical configuration features red soils (Luvisols) on crest and upper slope, shallow or moderately deep red soils (Leptosols and Cambisols) on steeper sections of the slope, and black Vertisols in lower positions.

Smectite is the first secondary mineral to form upon rock weathering in the semi-arid to sub-humid tropics. Smectitic clay retains most of the ions, notably Ca^{2+} and Mg^{2+}, liberated from weathering primary silicates. Iron, present as Fe^{2+} in primary minerals, is preserved in the smectite crystal lattice as Fe^{3+}. The smectites become unstable as weathering proceeds and basic cations and silica are removed by leaching. Fe^{3+}-compounds however remain in the soil, lending it a reddish colour; aluminium is retained in kaolinite and Al-oxides. Leached soil components accumulate at poorly drained, lower terrain positions where they precipitate and form new smectitic clays that remain stable as long as the pH is above neutral.

There are more reasons why there is a relative dominance of smectite in the lower members of the catena:

1. *fine clay* in which the proportion of smectites is greater than in coarse clay, is *transported laterally*, through surface and subsurface layers, and
2. *drainage and leaching of soluble compounds decrease* from high to low terrain positions. Internal drainage is impeded by the formation of smectites. (It is increased when kaolinite forms: ferric iron, released from the smectite lattice, cements soil particles to stable structural peds and maintains a permanent system of pores in the soil.)

The combined processes of *rock weathering*, *breakdown of primary minerals* and *formation of secondary minerals*, and *transport of soil components* produce the typical catenary differentiation with reddish, well-drained soils on higher positions, and black, poorly drained soils in depressions (see Table 1).

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2 a **catena** is a succession of soils developed from the same parent material and extending from a high position in the landscape to a low position.

Colour differences between Vertisols are often indicative of differences in drainage status. The more reddish hue or stronger chroma of relatively better-drained Vertisols reflects higher contents of free iron-oxides. Poorly drained Vertisols are low in kaolinite and have less free ferric iron; their hues are less red and their chromas are weaker.

TABLE 1
Some analytical data of the highest (Luvisol) and the lowest member (Vertisol) of a 'red-black' soil catena in the Sudan

PROFILE	ABC	DEPTH (cm)	CLAY (%)	pH	CEC	CECclay	BS (%)	SiO_2/Al_2O_3 (clay fr.)	OrgC (%)	Lime (%)
					(cmol(+)/kg)					
LUVISOL	A	0-10	4	6.6	Nd	Nd	Nd	3.8	0.5	0
	AB	10-30	15	6.1	9.0	60	71	3.3	0.6	0
	Bt1	30-60	23	4.7	15.5	68	49	3.5	0.3	0
	Bt2	60-85	33	4.5	21.4	66	45	3.3	0.3	0
	Bt3	85-105	43	4.5	22.6	50	51	3.1	0.2	0
	BC	105-135	39	4.4	27.4	69	47	3.0	0.1	0
	C	135-160	39	4.7	27.4	71	57	3.2	tr	0
VERTISOL	A	0-30	78	6.6	66.6	86	100	4.3	0.9	0.7
	Bw1	30-90	78	7.2	78.4	100	100	4.6	0.9	1.2
	Bw2	90-150	81	7.3	78.2	96	100	4.6	0.7	1.2
	BCwk	150-180	79	7.3	80.2	103	100	4.5	0.4	1.5

Formation of a vertic horizon

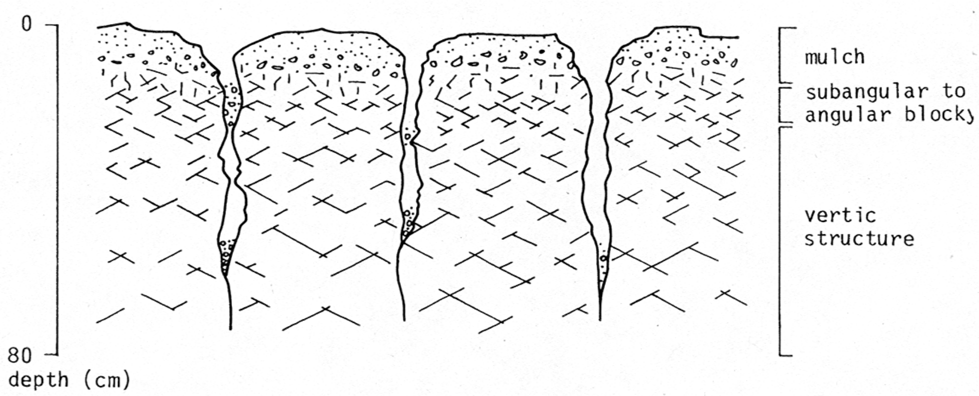
The formation of characteristic structural aggregates (*'vertic structure'*) is the principal genetic process in Vertisols. This typical structure may occur in most of the solum but has its strongest expression in the *'vertic horizon'*; the grade of development and the sizes of peds change only gradually with depth. In the following, the processes at work will be explained for a level plain with (smectitic) clayey sediments and a semi-arid tropical climate with a distinct rainy season.

Picture this: the clay plain is flooded at the end of the rainy season, but most of the standing water evaporates eventually. When the saturated surface soil starts to dry out, shrinkage of the clayey topsoil is initially one-dimensional and the soil surface subsides without cracking. Upon further drying, the soil loses its plasticity and tension builds up until the tensile strength of the soil material is locally exceeded and the soil cracks. Cracks are formed in a pattern that becomes finer as desiccation proceeds. In most Vertisols, the surface soil turns into a *'surface mulch'* with a granular or crumb structure. Vertisols, which develop surface mulch, are called *'self-mulching'*. See Figure 3.

Granules or crumbs of the mulch fall into cracks. Upon re-wetting, part of the space that the soil requires for its increased volume is occupied by mulch material. Continued water uptake generates pressures that result in shearing: the sliding of soil masses against each other.

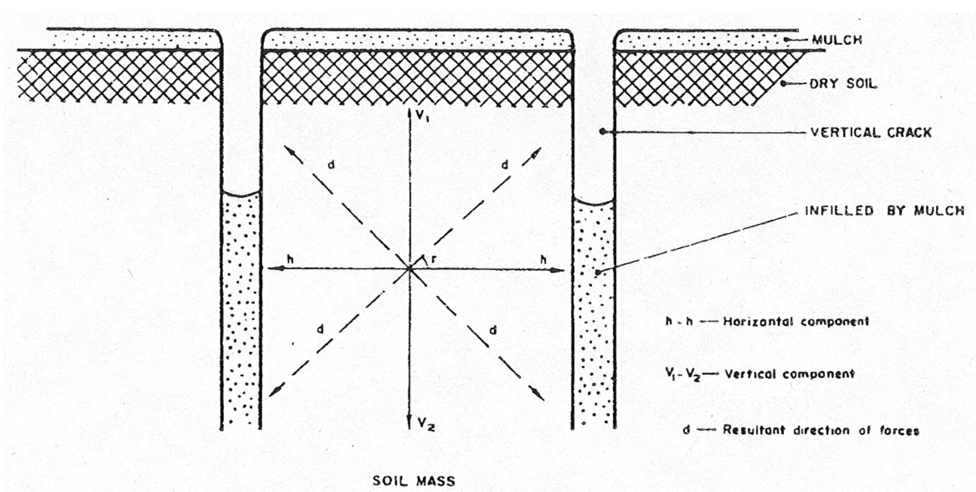
Shearing occurs as soon as the *'shear stress'* that acts upon a given volume of soil exceeds its *'shear strength'*. The swelling pressure acts in all directions. Mass movement along oblique planes at an angle of 20 to 30 degrees with the horizontal plane resolves this pressure

Figure 3
Cracks, surface mulch and soil structure in a Vertisol during the dry season



The shear planes are known as *'slickensides'*, polished surfaces that are grooved in the direction of shear. Such ped surfaces are known as *'pressure faces'*. Intersecting shear planes define wedge-shaped angular blocky peds. Although the structure conforms to the definition of an angular blocky structure, the specific shape of the peds has prompted authors to coin special names such as 'lentils', 'wedge-shaped peds', 'tilted wedges', 'parallelepipeds' and 'bicuneate peds'. The type of structure is also called 'lenticular' or 'bicuneate' but shall be referred to as *'vertic'* in this text. See also Figure 4.

Figure 4
Schematic stress diagram. Soil at three-dimensional expansion stage (source: De Vos & Virgo, 1969)



The size of the peds increases with depth. In uniform soil material this is attributable to:

1. the *moisture gradient* during drying and wetting. This gradient is steepest near the surface where small aggregates are formed in loose packing (*'mulch'*). The moisture gradient decreases with depth except around cracks where wetting and drying are much more rapid than in the interior of crack-bounded soil prisms.
2. the *increasing overburden*, i.e. the increasing load of the overlying soil. At greater depths, higher swelling pressures are needed to exceed the soil's shear strength. Such pressures can only be generated in a large volume of swelling soil material and, consequently, structural aggregates are larger.

The characteristic *vertic* horizon extends from some 15 or 20 cm below the surface mulch down to the transition from solum to substratum, i.e. just below the depth of cracking. Where there are no seasonal moisture changes in the substratum, the vertic structure is *fossil*. Vertisols with very deep, fossil, vertic horizons are common where sedimentation has alternated with periods of geogenetic standstill.

Sliding of crumb surface soil into cracks and the resultant shearing have important consequences:

1. Subsurface soil is pushed upwards as surface soil falls into the cracks. In this way surface soil and subsurface soil are mixed, a process known as 'churning' or (mechanical) 'pedoturbation'. Churning has long been considered an essential item in Vertisol formation. However, recent morphological studies and radiocarbon dating have shown that many Vertisols do not exhibit strong homogenization. In such Vertisols, shearing is not necessarily absent but it may be limited to up-and-down sliding of soil bodies along shear planes.
2. In churning Vertisols, coarse fragments such as quartz gravel and hard, rounded, carbonatic nodules are concentrated at the surface, leaving the solum virtually gravel free. The coarse fragments are pushed upwards with the swelling soil, but most of the desiccation fissures that develop in the dry season are too narrow to let them fall back.
3. Aggregates of soft powdery lime indicate absence of churning, unless such aggregates are very small and form rapidly. Soft powdery lime is a substratum feature in Vertisols.

Note that not all Vertisols develop a surface mulch; some develop a hard surface crust. Cracks in such soils are sharp-edged, remain open throughout the dry season, and little surface soil falls into them. Swelling pressures will still build up because of differential wetting between adjoining parts of soil. Therefore these soils do have a vertic structure but the grade of the structure is weaker than in self-mulching Vertisols.

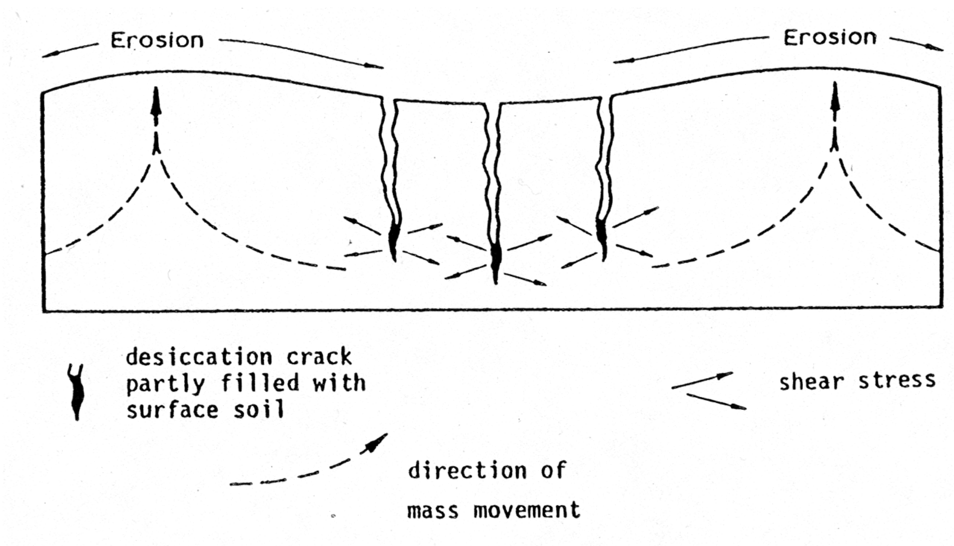
Crusty Vertisols are but one example of the variation in structure formation among Vertisols. Fine peds or, alternatively, cracks at close intervals, are generally formed in soil materials that have low tensile and shear strengths, whereas large peds (cracks at wider intervals) are formed in soil materials with high tensile and shear strengths. Vertisols that are rich in sodium have greater tensile and shear strengths than soils with lower sodium saturation; many of such soils have a surface crust rather than a mulch. If the exchangeable sodium percentage (ESP) is low and there is much finely divided lime, surface mulching is maximal and peds are fine. The processes that lead to a vertic structure become stronger with increasing clay content and with a higher proportion of swelling clay minerals. Sandy Vertisols have limited swell and shrink; they develop narrow cracks and a surface crust.

Formation of a 'gilgai' surface topography

A typical self-mulching Vertisol has an uneven surface topography: the edges of crack-bounded soil prisms crumble, whereas the centres are pushed upward. The scale of this surface irregularity is that of the cracking pattern, usually a few decimeters. 'Gilgai' however represents micro-relief at a larger scale, superimposed on this unevenness. Gilgai on level terrain consists of small mounds in a continuous pattern of small depressions, or depressions surrounded by a continuous network of narrow ridges.

Several hypotheses have been put forward to explain the gilgai micro-relief. These have in common that they relate gilgai to mass movement in swell/shrink soils. Gilgai is sometimes seen as the result of sloughing of surface mulch into cracks and upward thrust of soil between cracks upon subsurface soil swelling. However, gilgai is clearly superimposed over the cracking pattern; it originates in the subsurface soil and substratum. For gilgai to form, the soil must have sufficient cohesion to transfer pressures all the way to the soil surface.

Figure 5
Sketch showing the kinematics of mass movement in Vertisols that result in gilgai microrelief (after Beinroth, 1965)

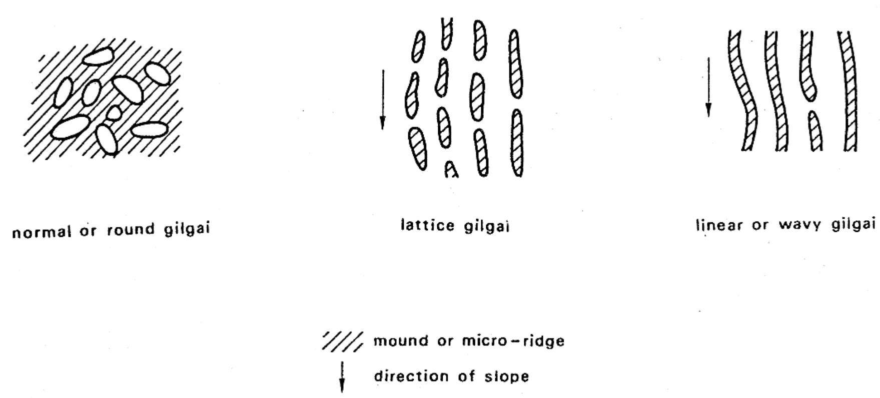


There are two observations to support a subsurface origin of gilgai micro-relief:

1. A trench profile through a complete 'wave' of mound and depression shows that slickensides in the lower solum and upper substratum are continuous from below the centre of the depression towards the (higher) centre of the mound. The oblique shear planes show a preferential direction. Substratum material is pushed upwards alongside such sets of parallel slickensides. See Figure 5.
2. A gilgaied land surface that is levelled will have gilgai reappearing in a few years.

The commonest form of gilgai is the 'normal' or 'round' gilgai. On slightly sloping terrain (0.5 to 2 percent slope) 'wavy' or 'linear' gilgai occurs; 'lattice' gilgai is a transitional form on very slight slopes. Wavy gilgai consists of parallel micro-ridges and micro-valleys that run with the slope, i.e. at right angles to the contours. The wavelength (from centre of mound to centre of depression) is between 2 and 8 m in most gilgais; the vertical interval or 'amplitudo' is normally between 15 and 50 cm. Figure 6 presents some common forms of gilgai.

Figure 6
Common forms of gilgai



Most gilgaied areas have Vertisols, but not all Vertisols develop a gilgai micro-relief. In the Sudan, Vertisols occur in a more or less continuous clay plain over a distance of some 700 km from north to south. The annual rainfall sum increases in that direction from 150 to 1000 mm. Gilgai micro-relief occurs only in the 500-1000 mm rainfall zone. Gilgaied Vertisols in the south have thinner and less clearly expressed surface mulch and are less calcareous than non-gilgaied Vertisols in the north.

The morphology of gilgaied Vertisols differs between mound and depression areas. The A-horizon is thin on mounds whereas profiles in depression areas have a deeper (thickened) and usually darker A-horizon. Coarse components of substratum material that reach the soil surface at the mound site, e.g. quartz gravel and carbonate concretions, remain at the surface whereas finer soil material is washed down to the depressions.

Note: 'High gilgais', with wavelengths up to 120 m and amplitudes of up to 240 cm, occur in Australia. These high gilgais may well have formed in an entirely different way.

CHARACTERISTICS OF VERTISOLS

Morphological characteristics

Vertisols have A(B)C-profiles; the A-horizon comprises both the surface mulch (or crust) and the underlying structured horizon that changes only gradually with depth. The subsurface soil with its distinct vertic structure conforms to the definition of a vertic horizon but it is not always clear where the A-horizon ends and the B-horizon begins. Important morphological characteristics such as soil colour, texture, element composition, etc are all uniform throughout the solum.

There is hardly any movement of soluble or colloidal soil components. (If such transport occurs, pedoturbation counteracts it.) A calcic horizon or a concentration of soft powdery lime may be present in or below the vertic horizon. Gypsum can occur as well, either uniformly distributed over the matrix or in nests of gypsum crystals.

Physical characteristics

Vertisols with strong pedoturbation have a uniform particle size distribution throughout the solum but texture may change sharply where the substratum is reached. Dry Vertisols have a very hard consistence; wet Vertisols are (very) plastic and sticky. It is generally true that Vertisols are friable only over a narrow moisture range but their physical properties are greatly influenced by soluble salts and/or adsorbed sodium.

Infiltration of water in dry (cracked) Vertisols with surface mulch or a fine tilth is initially rapid. However, once the surface soil is thoroughly wetted and cracks have closed, the rate of water infiltration becomes almost zero. (The very process of swell/shrink implies that pores are discontinuous and non-permanent.) If, at this stage, the rains continue (or irrigation is prolonged), Vertisols flood readily. The highest infiltration rates are measured on Vertisols that have a considerable shrink/swell capacity, but maintain a relatively fine class of structure. Not only the cracks transmit water from the (first) rains but also the open spaces between slickensided ped surfaces that developed as the peds shrunk.

Data on the water holding capacity of Vertisols vary widely, which may be attributed to the complex pore space dynamics. Water is adsobed at the clay surfaces and retained between crystal lattice layers. By and large, Vertisols are soils with good water holding properties. However, a large proportion of all water in Vertisols, and notably the water held between the basic crystal units, is not available to plants. Investigations in the Sudan Gezira have shown that the soil moisture content midway between large cracks changes very little, if at all, when the clay plain is flooded for several days or even several weeks. The soil's moisture content decreases gradually from more than 50 percent in the upper 20 cm layer to 30 percent at 50 cm depth. Deeper than 100 cm, the soil moisture content remains almost invariant throughout the year.

Chemical characteristics

Most Vertisols have a high cation exchange capacity (CEC) and a high base saturation percentage (BS). The soil reaction varies from weakly acid to weakly alkaline; pH-values are in the range 6.0 to 8.0. Higher pH values (8.0-9.5) were measured on Vertisols with much exchangeable sodium. The CEC of the soil material (in 1 M NH4OAc at pH 7.0) is commonly between 30 and 80 cmol(+)/kg of dry soil; the CEC of the clay is of the order of 50 to 100 cmol(+)/kg clay. The base saturation percentage is greater than 50 and often close to 100 percent with Ca^{2+} and Mg^{2+} occupying more than 90 percent of the exchange sites; the Ca/Mg-ratio is normally between 3 and 1.

Salic and *Natric* Vertisols are common in the more arid parts of the Vertisol coverage. In places, sodicity occurs also in higher-rainfall areas, e.g. in depressions without outlet. The effect of sodicity on the physical properties of Vertisols is still a subject of debate. As stated earlier, Na-clays have greater tensile and shear strengths than Ca-clays, and a high exchangeable sodium percentage (ESP) is associated with soil structure of a relatively coarse class.

The effect that a high ESP has on the diffuse double layer (wide double layer, hence low structure stability) is offset by the high ionic strength of the soil solution in Vertisols that are both saline and sodic. Clay dispersion accompanied by clay movement, the normal consequence of high sodium saturation in clay soils, cannot take place on account of the low hydraulic conductivity and low volume of soil that ever becomes saturated with water. Salinity in Vertisols may be inherited from the parent material or may be caused by irrigation. Leaching of excess salt is hardly possible. It is, however, possible to flush salts that have precipitated on the walls of cracks. Surface leaching of salts from rice paddies in India was achieved by evacuating the standing water at regular intervals. There are strong indications that the fallow year observed in rotations in the Gezira/Manaqil irrigation scheme in Sudan, is indispensable for maintaining a low salinity level in the surface soil.

Management/ use of Vertisols

Large areas of Vertisols in the semi-arid tropics are still unused or are used only for extensive grazing, wood chopping, charcoal burning and the like. These soils form a considerable agricultural potential but adapted management is a precondition for sustained production. The comparatively good chemical fertility and their occurrence in extensive level plains where reclamation and mechanical cultivation can be envisaged are assets of Vertisols. Their physical soil characteristics and notably their difficult water management cause problems.

Farming systems on Vertisols

The agricultural use of Vertisols ranges from very extensive (grazing, collection of fire wood, charcoal burning) through smallholder post-rainy season crop production (millet, sorghum, cotton, chick peas) to small-scale (rice) and large-scale irrigated agriculture (cotton, wheat, barley, sorghum, chickpeas, flax, noug (*Guzotia Abessynica*) and sugar cane). Cotton is known to perform well on Vertisols allegedly because cotton has a vertical root system that is not severely damaged by cracking of the soil. Tree crops are generally less successful because tree roots find it difficult to establish themselves in the subsoil and are damaged as the soil shrinks and swells. Management practices for crop production ought to be primarily directed at water control in combination with conservation or improvement of the soil's fertility level.

Physical land management on Vertisols

The physical properties and the soil moisture regime of Vertisols represent serious management constraints. The heavy soil texture and domination of expanding clay minerals result in a narrow soil moisture range between moisture stress and water excess. Tillage is hindered by stickiness when the soil is wet and by hardness when it is dry. The susceptibility of Vertisols to waterlogging is the single most important factor that reduces the actual growing period (below estimates based on climatic data). Excess water during the rainy season must be stored for post-rainy season use ('water harvesting') on Vertisols with very slow infiltration rates.

Several management practises have been devised to improve the water regime:

1. *Evacuation of excess surface water.* Surface drainage by using alternating broad beds and furrows, protects crops from water logging of the root zone. The drained water may be stored in small ponds and used for watering cattle, growing vegetables, etc. This practice proved very successful in the Ethiopian Highlands where the yields of local wheat varieties increased by 150 % and horse bean yields went up by 300 %. The only disadvantage of broad bed and furrow systems recognised so far is that they promote soil erosion by concentrating water flow in the furrows. The broad bed and furrow

technology solves problems on individual farmers' fields but solutions have still to be found to bring the runoff water safely down to the lowest part of the landscape (e.g. along grassed waterways) without enhancing erosion of neighbouring farmland. A participatory approach involving all stakeholders is needed to solve this problem at watershed scale.

2. *Gully control.* Containing gully erosion on Vertisols may require special dam constructions in the lower parts of the landscape, designed keep the groundwater table at a level that keeps the subsoil moist. In this way, swell-shrink is inactivated and many processes related to gully formation (slumping, pipe erosion, subsoil cracking) are curbed.
3. *Storage of excess water within the watershed.* If excess water is harvested behind micro dams, strategic irrigation of Vertisols downstream of the dam site becomes an option. Seepage losses from the dams may benefit the ecosystem as a whole, since the water will surface as recharge in lower landscape positions. Livestock benefit from these micro dams in several ways, e.g. by increased fodder availability from crop residues, presence of drinking water and increased fodder production in recharge zones. Even though micro dam projects are generally appreciated as successful, *salinisation* and *sodification* of the irrigation perimeters and *high percolation losses* are serious hazards. At some of the dam sites, up to 50 % of the harvested water is lost each year. This is a direct consequence of the swell-shrink behaviour of smectitic clays. The use of a membrane or of other construction materials, e.g. more weathered clay which may occur in the same landscape, has been suggested as a remedy. The build-up of soil salinity is a serious problem. In a mere decade, salinity may build up to the extent that the whole dam has to be demolished and the surrounding land left to regenerate for several years before it can be taken into cultivation again.
4. *Water harvesting in areas with Vertisols.* The deep and wide cracking of Vertisols retards wetting of the surface soil after a dry spell. Management should therefore be directed at storing water in the subsurface soil; the greater soil moisture reserves extend the possible length of a crop's growing period. Time-tested water harvesting techniques on Vertisols are:

   • *Construction of small ponds* for harvesting (drainage) water and keeping it in the higher parts of a watershed. This water can be used later, e.g. for strategic irrigation of vegetable gardens and/or for watering livestock.
   • *Contour ploughing and bunding* to enhance infiltration of water in the soil. A beneficial side effect of contour bunding is that it diminishes soil erosion, which is a severe problem of many Vertisols on slopes. In the highlands of Northern Ethiopia, continued contour ploughing resulted in stepped landscapes ('dagets') with step heights from 0.3 m to 3 metres. Grasses are planted on the riser and a strip of grass is maintained on the shoulder.
   • *Vertical mulching* to enhance infiltration of water in the subsoil. Stubble of crops is placed vertically in contour trenches with the stubble protruding 10 cm above the soil surface. Trenches are 4 to 5 metres apart.
   • *Construction of tied ridges,* as practised by farmers in Zimbabwe, to enhance infiltration of water in the subsoil. Note that this system can only be successful on strongly self-mulching Grumic Vertisols.

1. *Improvement of rooting conditions.* Several techniques to restore soil structure after many years of cultivation have been tried:

   • *Soil heating/burning* is practised in the Ethiopian highlands (the technique is locally known as '*guie*'). Burning causes the clay fraction to fuse to sand-sized particles.

- *'Flood fallowing'* (flooding the land for 6 to 9 months) has been tried on low-lying Vertisols. Gases produced by fermentation and redistribution of oxides improve rooting conditions in heavy clay surface soils.
- *Deep ploughing* of Vertisols with indurated horizons (e.g. some Calic and Gypsic Vertisols and Duric Vertisols) breaks the hardened subsoil.

Maintaining the nutrient status of Vertisols

Vertisols are considered to be among the most fertile soils of the seasonally dry tropics. The soils are rich in bases, with calcium and magnesium prevailing on the exchange complex. Many traditional farming systems observed a fallow period of 1 – 4 years in which Vertisols could restore the organic matter content of the surface soil after a period of intensive use. Increased population pressure has now reduced the proportion of fallow land (read: the fallow period) and many areas are left in fallow only when completely degraded. Trials have shown that continuous cropping can be sustainable provided that soil and water conservation and fertiliser management are adequate.

Many Vertisols are deficient in nitrogen, in line with their low organic matter content. Nitrogen fertilisers have to be applied in such a way that excessive volatilisation of ammoniacal nitrogen or leaching of nitrate ions are avoided. Placement of nitrate fertiliser in the root zone is best in dry regions whereas split banded application is preferred in wet conditions. If nitrogen is supplied in the ammonium form, the exchange complex of Vertisols, which curbs (leaching) losses, retains it. Many Vertisols have a low content of *available* phosphorus. In the East-African highlands, Vertisols on weathered basalt showed little response to application of phosphate under low-intensity farming but phosphorus became strongly limiting if farming was intensified (and yields went up). Acidic Alic Vertisols and Chromic Vertisols may contain much exchangeable aluminium and are notorious for inactivating fertiliser phosphate. In places Vertisols are low on sulphur and/or zinc.

It is generally believed that application of animal manure would improve soil organic matter and soil physical properties but trials remained largely inconclusive. Crop residues should be returned to the land but are used instead as animal feed, fuel and building materials. Trials with green manure (legumes) showed a remarkable increase of the yields of cereals and increased efficiency of mineral fertiliser uptake. Combining broad beds and furrows with application of phosphorus fertiliser and inter-cropping of cereals and legumes takes full benefit of crop-livestock interactions. The legumes overgrow the cereal stover after harvest (Jutzi et al., 1987; Gryseels, 1988).

Set #4

Mineral Soils conditioned by Topography

Major landforms in alluvial lowlands
Fluvisols
Gleysols
Major landforms in mountains and formerly glaciated regions
Leptosols
Regosols

Major landforms in alluvial lowlands

In the present context, the term *'lowlands'* refers to flat and level wetlands, *commonly* situated at or near sea level and consisting of mainly Holocene sediments that are too young to be strongly weathered. Such lowlands are prominent in landscapes with a fluvial, lacustrine, marine or glacial signature.

Tectonic processes during the past 10^5-10^6 years had a decisive influence on the formation of lowlands, in particular in subsidence areas such as sedimentary basins and '*grabens'* where rivers lose much of their transport capacity as the river gradient decreases. Loss of gradient forces many rivers to deposit their bed load and suspension load in their lower reaches.

Prominent sea-level changes and climate fluctuations occurred during the past 10^3-10^5 years. Sea level changes strongly influence river behaviour and coastal development. Climate changes affect the discharge and sediment load characteristics of rivers and also the development of a protective vegetation cover that stabilises the landscape. Changes in sea level and/or climate induce changes in river type, channel pattern and sediment sequences. Climate changes during the (recent) Quaternary had a particularly strong impact. In (now) temperate regions, glacial climate was much drier and colder than today. Wet-tropical areas were drier as well. A belt of permafrost surrounded the large continental ice sheets and sea levels were some 120 m and perhaps even 135 m lower than today. There are strong indications that mass wasting processes such as *frost weathering* and *'gelifluction'* in high-relief areas were more prominent than today and that consequently the sediment loads of rivers were greater than at present. Once most of the Pleistocene ice cover had disappeared, some 6,000 years ago, the rate of sea level rise decreased and coasts adapted to the higher sea level. Today, (Pleistocene) glaciers that have long disappeared still influence some 15 percent of the land surface. It is impossible to understand the complexity of 'landforms in lowlands' without referring to their present climate *and* their climatic history.

In the following discussion, the major landforms in alluvial lowlands will be aggregated to two broad categories:

1. *(inland) fluvial lowlands*, and
2. *(coastal) marine lowlands*.

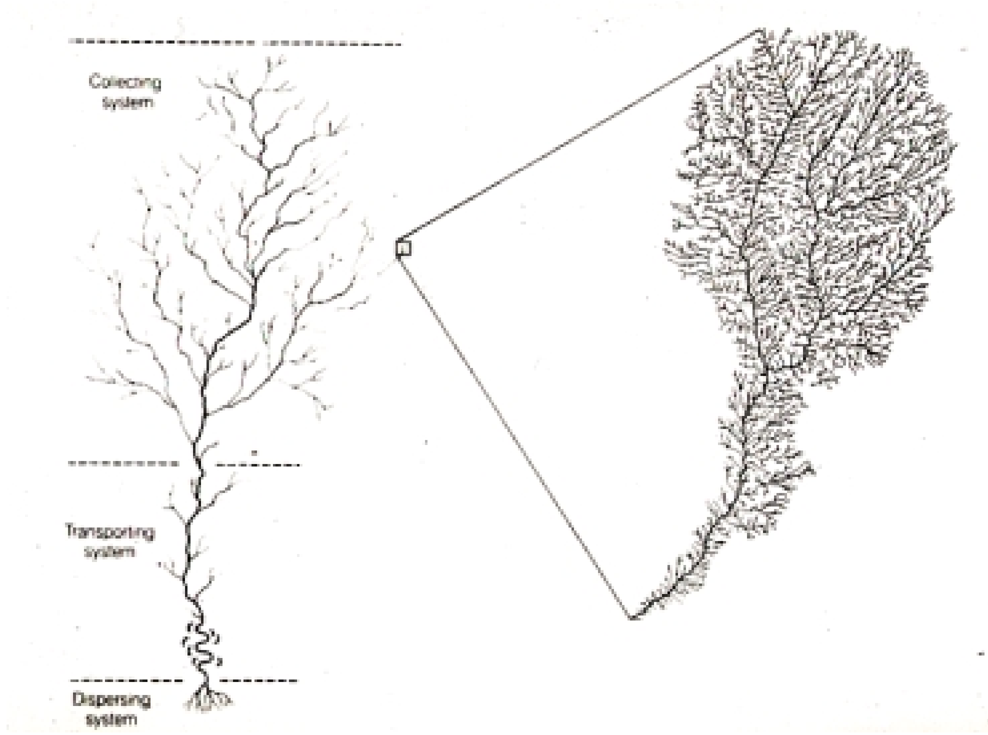
Landforms in inland fluvial lowlands

River systems are complex systems and a catchment area will normally harbour a variety of landforms. These vary with the nature of the river and with the position in the river system. In most river systems, three zones can be distinguished (see Figure 1):

1. the *upper reach* where erosion exceeds sediment deposition. This reach is normally characterised by active incision of the river and by V-shaped valleys in-between high hills or mountains that become gradually levelled by erosion. This reach will not be discussed here, as it is not part of the 'lowlands'.

2. the *middle reach*, in which erosion and deposition roughly compensate each other with predominance alternating in time. This reach is largely a zone of sediment bypass, or transport; rivers flow in their own alluvium and have either meandering or braided channels, in places with terraces or alluvial fans.
3. the *lower reach* with prolonged net sediment accumulation in a basin area. This zone usually grades into a delta, an estuary or some other coastal landform, or (in arid regions) fades away in an enclosed salt lake or dry basin.

Figure 1
The upper, middle and lower reaches of a river course



Tectonic uplift or subsidence, climate changes and sea level changes are external controls on river behaviour. The main variables that control a fluvial system are *gradient*, *discharge* and *sediment supply* to the drainage network. They determine whether a river incises or aggrades and which channel type is most efficient in dissipating kinetic energy. Three main river types or (better) channel patterns can be distinguished that differ in the number of channels and channel sinuosity:

1. *braided rivers*,
2. *meandering rivers*, and
3. anastomosing rivers.

Note that river systems are highly dynamic and that channel patterns adapt to changes in regional or local conditions. This means that different channel patterns and landforms may exist in the same fluvial system. For instance, the Yukon River in Alaska has a braided pattern in its upper reach, but assumes a meandering pattern in the lower reach in response to its sharply decreased gradient.

Braided rivers

Braided rivers have one single channel of low sinuosity and high gradient, with multiple '*thalwegs*' and bars. The bars are bare or vegetated sediment islands around which flow is diverted in the channel thalwegs. During times of maximum discharge, the channel is completely inundated and most of the bars conduct water. In times of low discharge, multiple thalwegs and bars reappear within the channel, which lets the braided river resemble a multiple-channel system. The pattern of bars and thalwegs may change profoundly during a flood stage, with vegetated bars remaining in place longer than barren ones.

Braided rivers occur in areas with

1. *a highly irregular water regime*, and
2. *abundant sediment supply*.

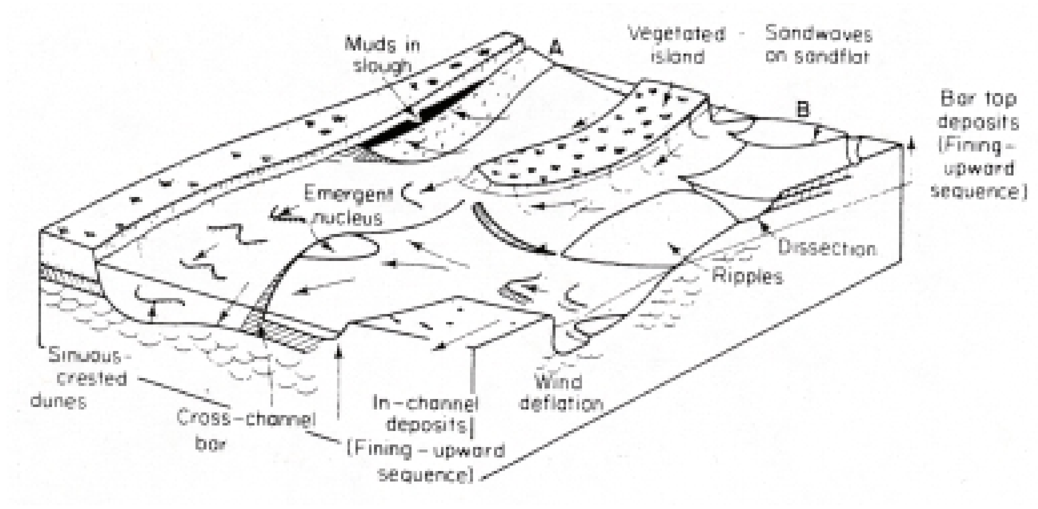
Such conditions are common in areas with sparse vegetation and torrential rains, e.g. in arid and semi-arid regions and in permafrost regions where sudden peaks in water and sediment discharge occur in spring when snow and ice melt. Braided rivers are particularly common near glacier fronts and in volcanic areas where glacier melting or volcanic eruptions are associated with sharp peaks in sediment supply.

Deposits by braided rivers contain alternating areas (lenses) of coarse gravel and sand with only minor inclusions of finer sediment. Gravel or coarse sand is preferentially deposited at the downstream ends of bars whereas the sides of bars are eroded as the thalwegs shift. Some braided rivers carry mainly sand and silt, e.g. the Yellow River in China and the Brahmaputra river in Bangladesh. Braided river deposits may become covered with a layer of fine-grained sediments (*'overbank deposits'*, also referred to as 'Hochflutlehm') once the river incises into deeper layers by deepening a major thalweg. Its former floodplain has then become a *terrace*. Overbank deposits are further thickened during exceptionally high floods of the incised and (often) already meandering river. Former gravel bars and gullies can normally still be seen in the micro-relief (less than a metre high) of areas underlain by braided river deposits. Figure 2 shows the basic elements of a typical braided river system.

Some authors consider *'alluvial fans'* as a special type of braided river. Nichols (1999) defined them as cones of detritus that form at a break in slope at the edge of an alluvial plain. Alluvial fans are not uncommon in humid regions but truly classical examples are found in arid regions such as Death Valley in Arizona, USA. Alluvial fans are therefore discussed in the chapter on landforms in arid regions. Some highlights:

Alluvial fans have a steep gradient and their unconfined channels shift frequently over the depositional cone. They develop at places where river gradients decrease sharply, for instance at mountain fronts where a tributary stream leaves the mountains and enters a level alluvial plain. The sediment load of the feeding river can no longer be carried and most of it is dropped right at the entrance to the plain. This rapidly blocks the channel, which then sweeps left and right to obviate the obstacle. Deposits tend to be coarser on the *'proximal'* part of the fan (close to the apex) than on the *'distal'* part (far into the plain). In contrast with 'normal' braided river systems, mudflows are common on alluvial fans; their deposits are most numerous near the apex of the fan.

Figure 2
Basic elements of the South Saskatchewan River, a typical braided river. Bar A is driven toward the far bank, forming a protected part of the channel (slough) in which mud is deposited. B is a complex sand flat. Source: Blatt, Middleton & Murray, 1972; based on work by D.J. Cant



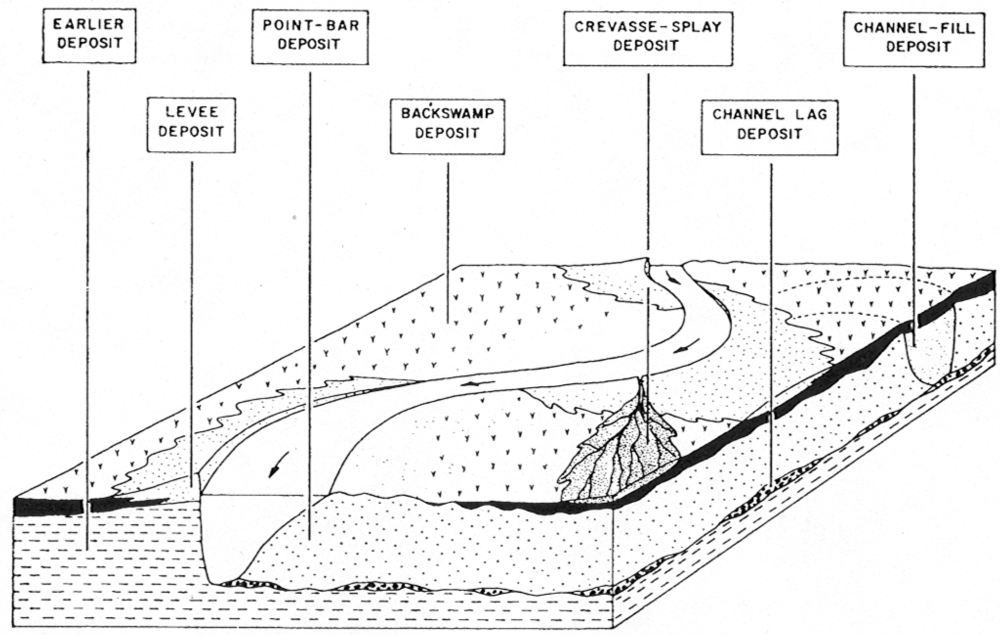
Meandering rivers

Meandering rivers consist of one single channel and thalweg, with a low gradient and high sinuosity. Sediments are preferentially deposited at the inner sides of meander bends. The channel is bordered by *'natural levees'* behind which *'flood basins'* or *'backswamps'* occur. Laboratory experiments have confirmed that meandering channels are typical of rivers with rather steady discharge rates and sediment loads of relatively fine-grained material (sand, silt, clay). See Figure 3.

Meandering rivers are associated with vegetated areas under a humid climate where a dense vegetation cover curbs erosion. All this favours *chemical* weathering and formation of fine-grained soil material. Surface run-off is minimal and the river is fed by a steady base flow of groundwater. Note, however, that meandering river stretches are also found in cold regions (e.g. the lower Yukon River, Alaska). Meandering rivers do occur in arid environments but their sources are invariably outside the arid region. The rivers Euphrates and Tigris, for instance, originate in the snow-capped Taurus mountain range, Turkey, before they reach the Mesopotamian desert.

The discharge rate of a meandering river may fluctuate considerably over time, in line with seasonal fluctuations in rainfall, snow melt and evapotranspiration but the river runs never dry and frequent floods are uncommon. If the channel is filled to the top of its natural levees, the river is said to be at *'bank-full stage'*. When more water is supplied than can be held between the levees, the river spills into its basins and floods its backswamp areas.

Figure 3
The classical meandering stream. Source: Allen, 1964



Deposition of sediments takes place in the channel, on the levees and in the basins. Gravel and coarse sand are normally found on the channel floor (*'lag deposits'*). Finer sand settles along the inner bends of the river, on so-called *'point bars'*. During floods, fine sand or silt is deposited on top of the levees, and clay in the basins. (Peat may accumulate there as well, at the lowest/wettest positions in situations of low clastic input.)

The whole system of gravely lag deposits, sandy pointbars, sandy/silty levees and clayey back-swamps shifts laterally as the meandering channel erodes the outer banks and deposits sediments on the inner-bend point bars. A 'fining-upwards' sedimentary sequence may develop in this way. '*Crevasse splays*' formed when the river breaks through its levees and spills abruptly into a basin area during a flood, do not show the fining-upwards sequence. Eventually, meandering leads to channel cut-offs (so-called *'oxbow lakes'*), which become filled in with clay and/or peat.

Anastomosing rivers

Anastomosing rivers have multiple, interconnected channels that divide and rejoin around relatively stable areas of floodplain (in the case of lowland rivers) or bedrock (in upland streams). Anastomosing rivers differ from multiple-thalweg braided rivers in that the river has only one thalweg *without* bars. The river gradient is typically very low; the channels have stable banks and channel *'avulsion'* is common. Avulsion is the breaking of a river (channel) through its natural levees to find a new course in a lower part of the floodplain. The channel downstream of the point of avulsion may become an abandoned 'paleo-channel' but in anastomosed river systems old channels normally remain active.

The very low gradient of anatomosed river reaches interferes with water discharge in times of floods: *crevasse splays* are abundant. These are sandy outwash fans that develop when the river breaks through its levee without forming a new channel. Crevasse deposits are predominantly clayey and silty in texture because the low gradient of the anastomosing river precludes transport of coarser particles. For the same reason, levees consist of fine sand and silt. Basin areas are filled in with clay and peat. Anastomosing rivers are typically found inside or near deltas or areas close to the coast such as the Late Holocene Rhine-Meuse delta in the Netherlands. Anastomosing rivers occur also in rapidly subsiding inland basins; examples are the Lower Magdalena Basin in Colombia and the river Niger south of Timbuktu in Mali.

Landforms in coastal lowlands

Coastal lowlands contain a variety of landforms. Most of these are geologically young because the rapid post-glacial sea-level rise stabilised only some 6000 years ago. However, borings suggest that many deposits in fluvial deltaic plains and their marine counterparts had a long and turbulent history that was strongly influenced by sea-level fluctuations and changes in climate. Especially inundated, low-gradient continental shelves have complex histories. Some examples: the courses of the rivers Thames, Rhine-Meuse and Seine extended on the (then exposed) North Sea floor during glacial periods. They were tributaries to a big Channel River system, the delta of which was located far to the west of the present 'English Channel' area. This indicates that deltas may shift laterally over tens or even hundreds of kilometres. Today's coastal landforms are quite recent; their formation and properties depend in part on whether fluvial processes interact/interacted with marine processes or not. In the first case, deltas and estuaries are the major landforms. In the second case, we distinguish between depositional and eroding coastlines. Three land-shaping factors are important (apart from global sea level fluctuations):

1. the *input of fluvial water and sediment* in relation to marine redistribution,
2. the *energy of waves and currents*, and
3. the *amplitude of the tides* ('tidal range')

The combined actions of fluvial and marine processes determine whether or not a depositional body can form at the mouth of a river and what kind of body will form. If the rate of fluvial input of sediment exceeds marine sediment redistribution, the depositional sequence will 'prograde' seawards to form a '*delta*'. If marine redistribution can handle the input of fluvial sediments, a depositional body may develop that is not prograding, but only aggrading: an '*estuary*'. The actions of waves and tides determine which type of delta, estuary or coastline is formed, and the landforms that occur. By and large, tidal regimes can be divided into three broad categories:

1. the *'microtidal'* regime with a tidal range of < 2 m,
2. the *'mesotidal'* regime with a tidal range between 2 and 4 m, and
3. the *'macrotidal'* regime with a tidal range of >4 m.

Deltas

Deltas are prograding depositional bodies that form at the point where a river debauches in a lake or sea. The various sedimentary facies of delta bodies are indicative of one or more of the following (external) factors:

1. *water and sediment yield* of the fluvial system feeding the delta (climate, tectonics),
2. *seasonal changes* in water level and sediment yield (climate),
3. *river-mouth processes* (differences in river/sea water densities, buoyancy),
4. *coastal configuration*, mainly shelf slope and topography (delta gradient),

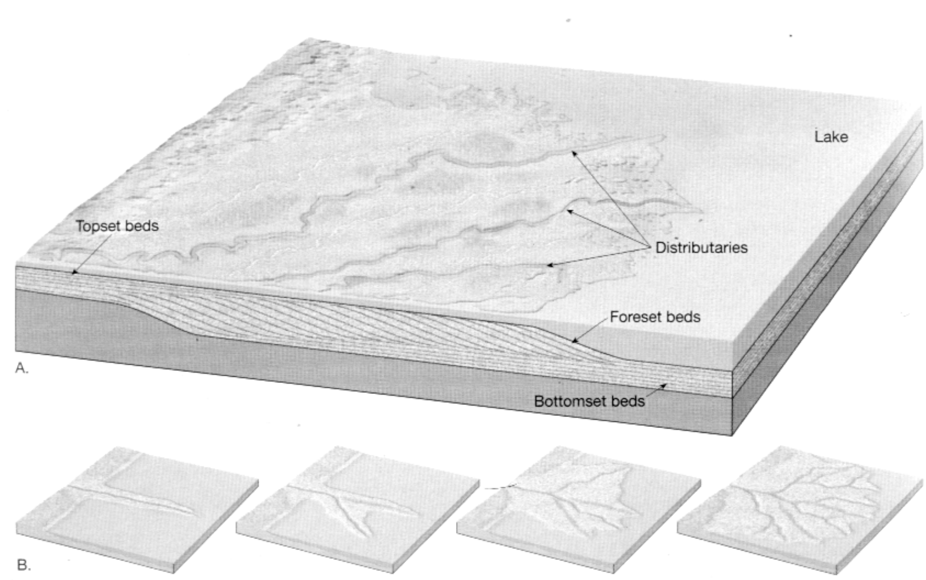
5. *wave and tidal energy* acting on the coast (climate, gradient, tidal range),
6. along shore winds and currents,
7. geometry and tectonics (subsidence) of the receiving basin.

Basically, 3 types of delta are distinguished:

1. *river-dominated deltas,*
2. *wave-dominated deltas*, and
3. *tide-dominated deltas*.

In *river–dominated deltas,* fluvial processes outweigh the influence of waves and tides. These deltas typically form in a microtidal regime at low coastal-shelf gradients. The low-gradient delta of the river Wolga (Russia) is a good example. The river Wolga drains into the Caspian Sea, which actually is not a sea but a fresh-water lake. Wave and tidal action are all but absent and fluvial processes shape the delta. Another classical example is the delta formed by glacially fed rivers debauching into the former (Late Glacial) Lake Bonneville (first described in 1885). Because no differences exist in the apparent densities of river water and lake water, and because the influence of waves and tides is negligible, a fan-shaped *'Gilbert-type delta'* is formed. In such river-dominated deltas, the coarsest (sand-sized) material is deposited in the *'delta plain'* close to the mouth. Finer (silty) sediments accumulate in the submerged *'delta slope'* and the finest (clay) particles travel farthest, to the *'prodelta'*. Thus, a gradation of grain sizes evolves across the delta. When the delta progrades under continuing sediment supply, progressively coarser sediments cover (or 'onlap' as sedimentologists say) the finer sediments: a coarsening-upwards sedimentary sequence is the result. Such sequences may be tens or even hundreds of metres thick. The fine prodelta sediments are called *'bottom-set beds'*, the sloping delta-front sediments are termed *'fore-set beds'*, and the topmost delta plain sediments are the *'top-set beds'*.

Figure 4
Outline of the basic structure of deltas



The Mississippi River delta is a special, river-dominated delta. The considerable discharge and sediment load of the Mississippi River lead to rapidly extending channel levees and transport of suspended sediment far into the Gulf of Mexico. The system expands to form a *'birdfoot delta'*, in which the distribution channels of the delta plain form the 'toes' of the foot. They even continue below sea level as sub-aqueous pro-delta channels. Swamp lands and coastal marsh form between the toes; they are the brackish equivalents of backswamps in purely fluvial environments. Occasionally, a channel breaks through its levees and deposits a *'crevasse splay'*: a small-scale fining-upwards sequence within the large-scale coarsening-upwards system. Because the channels transverse a very low-gradient delta plain, avulsions are frequent. When this happens, channels are abandoned and a new channel shifts laterally over the delta-plain: old delta lobes are left and new ones are built. See Figure 5 for illustrating block diagrams.

The second main type of delta is the *wave-dominated* river delta. Wave-dominated river deltas form in micro-tidal coastal regions where the coastal shelf has a steep gradient. Only then can waves attain the energy needed to attack and dissipate freshly deposited fluvial sediments. (*Note that* sub-aqueous prodelta channels cannot form!) If the main direction of the wind is perpendicular to the main delta axis, fluvial sediments will be redistributed laterally, in mouth bars and sandy beach ridges parallel to the coast. As a consequence, 'wave-influenced delta plains' have commonly cuspate or straight outlines. Lagoons form in-between the beach ridges and aeolian dunes may develop on the ridges themselves. The deltas of the rivers Rhône, Ebro and Nile in the Mediterranean Sea, and of the river Danube in the Black Sea are examples of wave-dominated deltas.

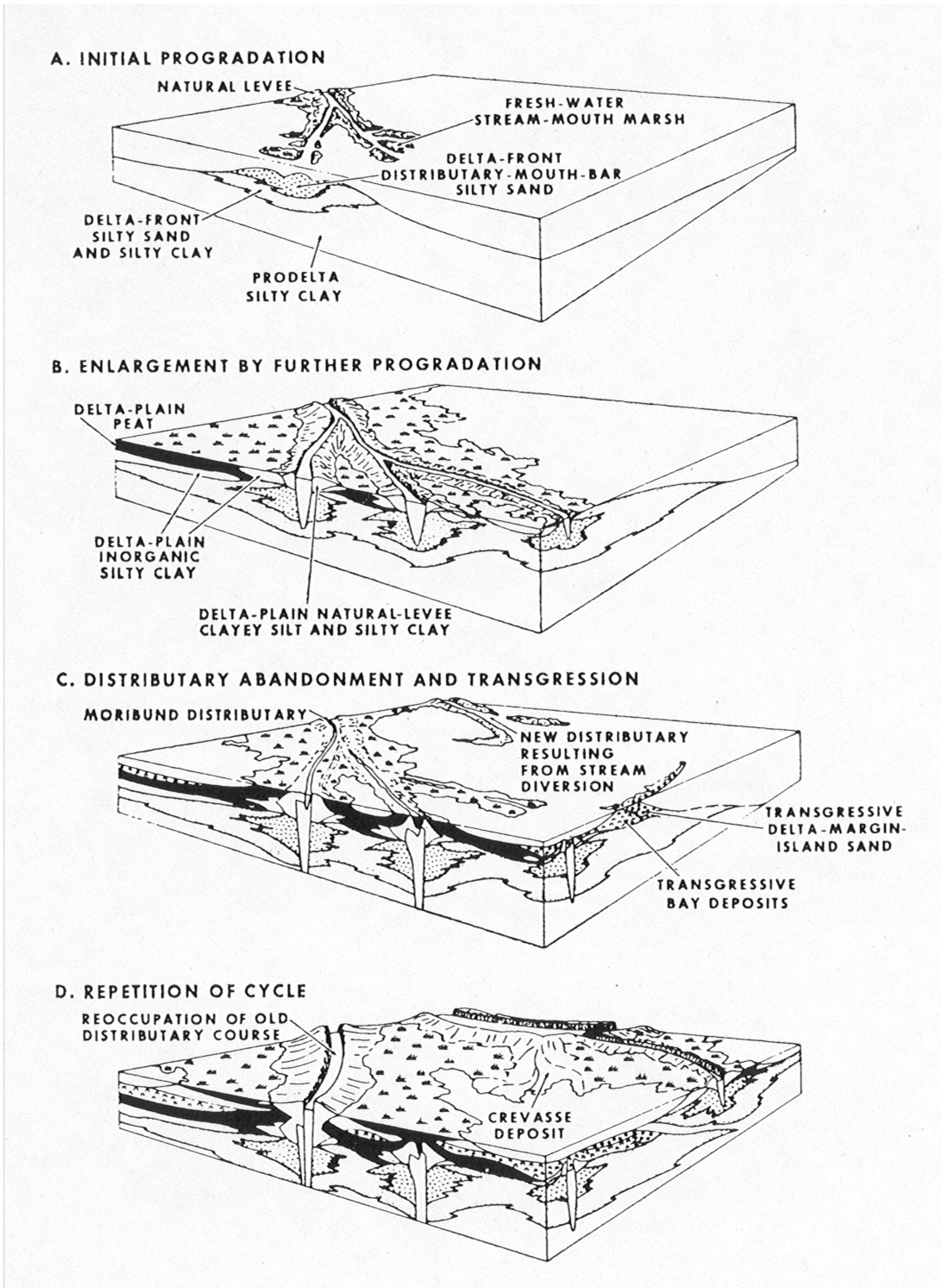
Under a meso-or macrotidal regime, ebb- and flood-tide currents are strong enough to scour fluvial channels and redeposit fluvial sediments in them. If the delta is still prograding, a *tide-dominated* river delta forms. The tidal currents widen the channels in the delta plain and sediments are deposited in opposite directions. The delta plain itself consists of tidal channels that have the shape of funnels widening in seaward direction, with tidal flats on the overbank areas between channels. In the tropics, the tidal flats are normally colonised by mangroves, which add much organic debris to the fresh sediment. Sandy mouth bars develop at the delta front, perpendicular to the coastline and parallel to the tidal currents. The deltas of the Mekong and Ganges-Brahmaputra river systems are tide-dominated delta plains. The Shatt al Arab delta (combined Tigris-Euphrates system) is a prograding tide-dominated delta in an arid region.

Estuaries

Estuaries are aggrading depositional sedimentary bodies at the mouths of rivers. Many present river mouths became estuaries after the post-glacial sea-level rise inundated the former deltas. When that happened, fluvial channels became subject to tidal influence. Especially in meso- and macro-tidal regimes, the fluvial processes became subordinate to marine redistribution and *tide-dominated* estuaries could form.

The major landforms in an estuary are *tidal channels and creeks*, in which predominantly sand is transported and deposited. In between them, *tidal mudflats* develop as a result of silt and clay deposition. The mudflats are flooded at high tide and fall dry again at low tide, when the suspended load stays behind as *'slackwater deposits'*. The mudflats are strongly saline, with halophytic vegetation on their most stable parts. Any vegetation helps to trap more sediment, which explains why overgrown mudflats grow faster than barren ones. In temperate climates, grasses are the main colonisers of mudflats whereas in tropical climates mangrove trees, with

Figure 5
Development of delta sequences in the Mississippi delta. Source: Frazier, 1967



their air roots are the principal species. Mudflats in arid regions may fall dry for several months each year, which may result in net accumulation of evaporites. The Rhine-Meuse and Thames fluvial systems are examples of estuarine, now tide- dominated river mouths.

Coastal landforms

Where coastal land is eroded or clastic deposits are reworked without any fluvial influence, a marine coastline will form, shaped exclusively by the combined actions of waves and tides. A coastline demarcates the boundary between net erosion of the exposed earth surface and net deposition in the marine realm. As the sea level has fluctuated strongly during past glacial and interglacial periods, coastal landforms may be inherited and reflect former sea levels. Three types of coastline can be distinguished:

1. *Drowned or uplifted coasts*, with landforms conditioned by sea level fluctuations,
2. *Erosional coastlines*, with marine erosion as the major land shaping force, and
3. *Depositional* or *constructional coastlines*, with adequate sediment supply.

Drowned or uplifted coasts, with landforms conditioned by sea level fluctuations. During the penultimate interglacial (Eemian), the sea level was 6 m higher than it is today. Former coastlines that were equilibrated to this higher sea level indicate that gravely and sandy sediments were deposited. When the sea level fell again, these sediments became exposed to form marine terraces. A similar course of events took place along tectonically or isostatically uplifting coasts. For instance, coral reef terraces are found on the tectonically uplifted Huon Pensinsula of Papua New Guinea. These (terraces) have been dated to the Late Quaternary sea-level fluctuations. Raised beaches of up to 9000 years old are present on the Baltic Shield, which experienced strong isostatic uplift after the Scandinavian ice sheet disappeared.

During the last Pleistocene glaciation (the *Weichselian*), the sea level was 120 metres lower than today. Large parts of continental shelves fell dry. As the base levels of erosion and ground water levels were lower as well, rivers in upland areas could form deeply incised river valleys. The lower reaches of these river valleys became inundated with seawater during the subsequent post-glacial sea level rise, which gave coasts a variety of shapes. '*Fjord coasts'* formed in glaciated regions when the glaciers retreated from their U-shaped valleys that were inundated when the sea level rose. *'Ria coasts'* and '*channel coasts'* were formed in non-glaciated areas where sediment deposition in the lower river reaches was insufficient to match the rise in sea level and keep the sea out of the valleys. A ria coast (e.g. SW-Ireland) has valleys perpendicular to the coastline, whereas valleys run parallel to the coastline of a channel coast (e.g. the Dalmatian coast).

Erosional coastlines, with marine erosion as the major agent form where clastic sediment supply is low and wave attack and along-shore currents move detritus away from the coastline. Typically, a '*cliff-face'* is eroded away along rocky shores whereas the coastline retreats along former depositional beaches. Undermining of the cliff-face by high-energy waves is the main erosion process along rocky shores. Strong winds associated with hurricanes or deep extra-tropical depressions provide the required wave energy. Salt weathering assists in loosening the rocks as sea-salt crystallises in cracks and fissures. Calcium-carbonate dissolution accelerates erosion of calcareous rocks. Prolonged undermining lets entire blocks or coastline sections slump into the sea. The white cliffs of Dover with their *'abrasion platforms'* covered with flint and limestone pebbles are a good example. Individual 'left-over' rocks stand out as *arches* or *stacks* along the coast.

Depositional or constructional coastlines, with adequate sediment supply are stable or prograding coastlines where accumulation of clastic sediments outweighs erosion by the sea. Whether accretion will take place or transgression depends on such factors as along-shore sediment supply, slope of the foreshore and subsidence rate of the basin. All these factors influence sedimentary sequences. The clastic material may be provided by nearby rivers and transported by along-shore currents, or eroding stretches of upstream coastline may be the source of sediment material. Degrading or eroding coral reefs in tropical shallow seas provide limestone weathering and other bioclastic debris. In very arid regions, evaporites make up much of the beach deposits. The relative influences of sediment supply, waves and tides determine the shape of depostional coastal landforms. The tidal range is (again) important: coasts with a tidal amplitude of 2 metres or less are called '*microtidal*', coasts with 2 to 4 metres tidal amplitude are '*mesotidal*' and coasts with a tidal amplitude of more than 4 metres are '*macrotidal*' coasts.

Microtidal coasts

Wave action rather than tidal action shapes microtidal coasts. Waves rolling up to the coast produce a surf (wash and backwash) resulting in net transport of sediment towards the coast. Compensating currents parallel to the shore are known as *'longshore currents'*. If the waves approach the coast under an angle, longshore currents and *'beach drift'* move sediment parallel to the coast. Wave-dominated microtidal coasts can have beach deposits attached to the hinterland or deposits can be separated from the hinterland by a narrow strip of sea, a *'lagoon*'.

Characteristic landforms of an *attached beach* are:

1. The *beach ridge* itself, i.e. the narrow strip of beach that is washed by waves breaking on the coast, with a *strand plain* (dry during ebb-tide) behind it. If the coastline is prograding, multiple relict beach ridges may be present, separated by old strand plains. These relict beach ridges are called *'chenier ridges'*, and the plains *'chenier plains'*. Examples of coasts with chenier plains are the coasts of the Guianas and the coast of Louisiana. The Surinam chenier plain has grown seaward over tens of kilometres during the past 6000 years.
2. *Beach dune ridges* are formed by beach sand that is blown away and deposited by the wind in ribbons parallel to the coast. Beach dune ridges may extend over hundreds of metres to kilometres inland and are commonly stabilised by grass vegetation.

Typical landforms of a *detached beach* are:

1. The *beach barrier*. If the beach barrier is attached to the mainland on one side, it is called a *'spit'*. If the barrier is not attached on either side, it is called a *'barrier island'*.
2. Behind the beach barrier lies a more or less protected water mass: the *'lagoon'*.
3. Most beach barrier ridges are interrupted to allow seawater to enter the lagoon at high tide and leave at low tide. These breaks are '*tidal inlets'*. An *'ebb-tidal'* or *'flood-tidal'* delta may form at the entrance of a tidal inlet/outlet depending on the strength of tides and waves.

The Dutch central coast, between Hoek van Holland and Den Helder, illustrates the formation of wave-dominated coastal lowland (the present tidal amplitude is only 1.5 metres). When the post-glacial sea level rise was still rapid, between 9,000 and 5,000 years BP, coastal formation was dominated by the tides. Then present beach barrier islands moved inland (during the transgression). Tidal inlets behind which clayey tidal flats were formed, the 'Calais deposits', separated them. On the landward side, the Calais deposits interfinger with fluvial clays and peat. When the rise in sea level slowed down (5000-2000 years BP), the barrier system closed. A wave-dominated coast formed and grew seawards. The relict beach ridges ('Old Barriers', 'Oude Strandwallen') and strand plains between them are particularly well developed in the stretch between the cities of The Hague and Haarlem. The slow rise of the groundwater level during this period created ideal conditions for accumulation of thick layers of peat (the 'Holland peat') on top of the Calais deposits. Much of the peat was later mined for fuel, until the Calais deposits were reached. The resulting lakes have later been drained and form the lowest polders of The Netherlands.

Meso- and macrotidal ('tide-dominated') coasts

Rivers debauching on meso- and macrotidal coasts have mouths that are strongly widened by incoming tides. It was mentioned earlier that estuaries have funnel-shaped channels separated by extensive tidal flats that are commonly brackish or saline. Where tides are high enough to flood large parts of a depositional coast, they build tidal flats. The Dutch-German-Danish Wadden Coast with a mesotidal range of 2-4 metres is a case in point.

Because tidal range conditions coastal development, the landforms found resemble those in estuaries. The tides enter and leave the tidal flats through *deep tidal inlets* between kilometre-scale *barrier islands*. E*bb-tidal* and *flood-tidal deltas* may form near the inlets as in lagoons. The tidal channels are permanently submerged and conduct huge masses of seawater and (coarse) sediment at incoming and outgoing tides. The sediment reaches the interior parts of the flats through small gullies and creeks (Dutch: *'prielen'*). These meander and widen towards their mouths. The *'intertidal mudflats'* (Dutch: *'platen'*) between mean high water level and mean low water level become submerged twice a day. Fine sandy and clayey material settles on these flats. The highest parts are flooded only during extreme spring tides; they are called *'supratidal mudflats'* (Dutch: *'kwelders'*, *'schorren'*).

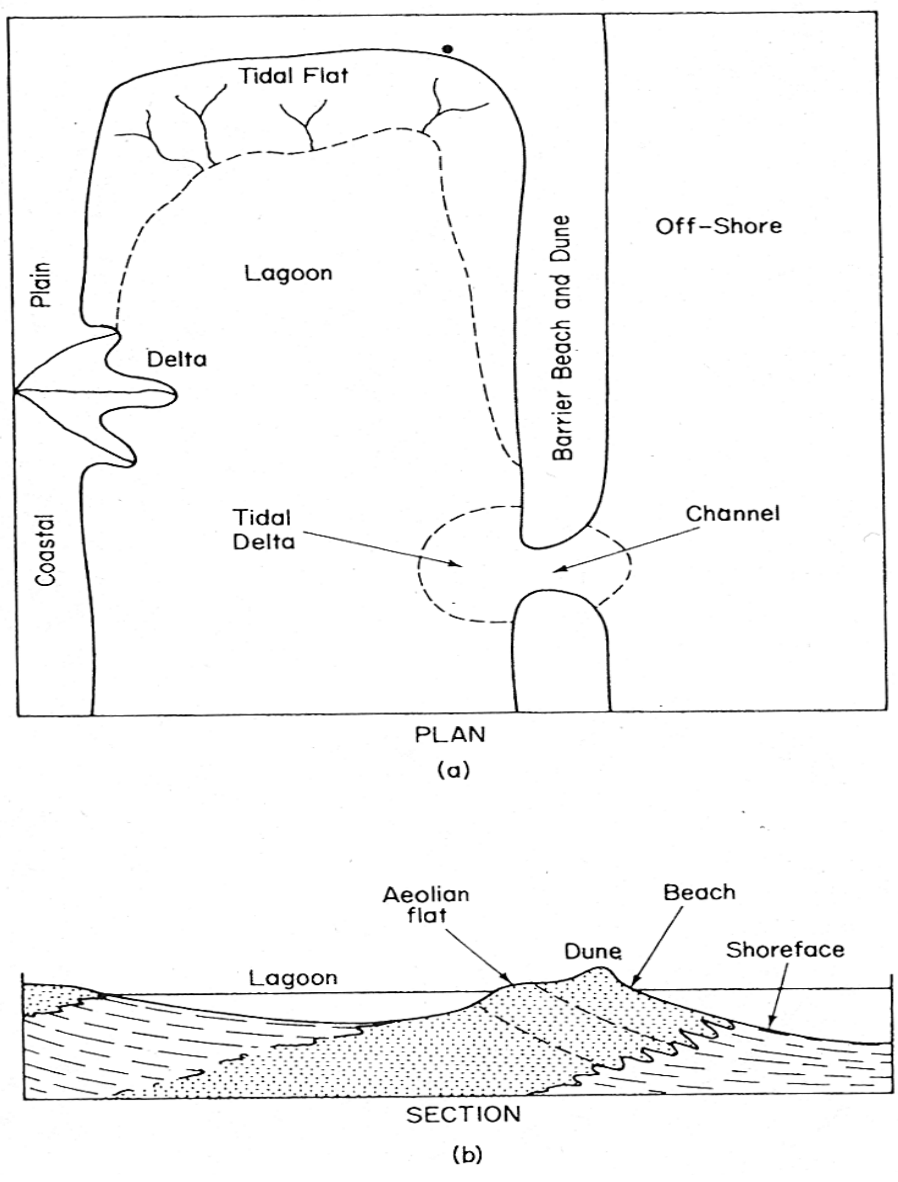
In temperate regions, intertidal flats are normally barren whereas supratidal flats carry a halophytic vegetation of grasses, herbs and shrubs. This vegetation traps sediment when flooded; the resulting deposits are stratified with a typical alternation of fine and coarse layers (Dutch: *'kweldergelaagdheid'*). Tidal flats in the humid tropics carry a mangrove vegetation already in the intertidal zone and silt up much more rapidly than most supratidal flats in temperate regions. Shifting of creeks and gullies leads to fining-upwards sequences, with fine supratidal and intertidal sediments on top of coarser creek and gully sediments.

Seaward progradation is associated with coarsening-upwards sequences, with the sea bottom consisting of finer material than sediments added and with finer-grained sands near the shoreline than higher up. Alternatively, barriers may shift landwards and sand may be deposited on top of older lagoon material producing coarsening upwards sequences. Interpretation of sedimentary patterns in the field is complicated by the fact that regression and progradation have in places alternated during the Holocene. Figure 6 presents an outline of the main morphological components of the barrier model.

By and large, soils in alluvial lowlands show signs of prolonged wetness and young age. Where sedimentation is still going on, stratified Fluvisols may be expected. Gleysols are found in depression areas that do not receive regular additions of sediment; their profiles testify of a shallow water table during all or most of the year.

In places, Histosols, Arenosols, Solonchaks or/or Solonetz may occur in alluvial lowland areas; these Reference Soil Groups are discussed elsewhere is this text.

Figure 6
Main morphological components of the barrier model.
Source: Blatt, Middleton & Murray, 1972



FLUVISOLS (FL)

(with special attention for Thionic Fluvisols)

The Reference Soil Group of the Fluvisols accommodates genetically young, azonal soils in alluvial deposits. The name 'Fluvisols' is misleading in the sense that these soils are not confined to *river* sediments (L. *fluvius* means 'river') but occur also in lacustrine and marine deposits. Many international soil names refer to this group, for example: 'Alluvial soils' (Russia, Australia), 'Fluvents' (USDA Soil Taxonomy), 'Fluvisols' (FAO), Auenböden (Germany) and 'Sols minéraux bruts d'apport alluvial ou colluvial' or 'Sols peu évolués non climatiques d'apport alluvial ou colluvial' (France).

Definition of Fluvisols[#]

Soils having

1. a thickness of 25 cm or more, and
2. *fluvic*[@] soil material starting within 50 cm from the soil surface and continuing to a depth of at least 50 cm from the soil surface; and
3. no diagnostic horizons other than a *histic*[@], *mollic*[@], *ochric*[@], *takyric*[@], *umbric*[@], *yermic*[@], *salic*[@] or *sulfuric*[@] horizon.

Common soil units:

Thionic*, Histic*, Gelic*, Salic*, Gleyic*, Mollic*, Umbric*, Arenic*, Tephric*, Stagnic*, Humic*, Gypsiric*, Calcaric*, Takyric*, Yermic*, Aridic*, Skeletic*, Sodic*, Dystric*, Eutric*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups.
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Fluvisols

Connotation: soils developed in alluvial deposits; from L. *fluvius*, river.

Parent material: (predominantly) recent, fluvial, lacustrine or marine deposits.

Environment: periodically flooded areas (unless empoldered) of alluvial plains, river fans, valleys and (tidal) marshes, on all continents and in all climate zones.

Profile development: AC-profiles with evidence of stratification; weak horizon differentiation but a distinct Ah-horizon may be present. *Redoximorphic* features are common, in particular in the lower part of the profile.

Use: Fluvisols are planted to annual crops and orchards and many are used for grazing. Flood control, drainage and/or irrigation are normally required. Thionic Fluvisols suffer from severe soil acidity and high levels of noxious Al-ions.

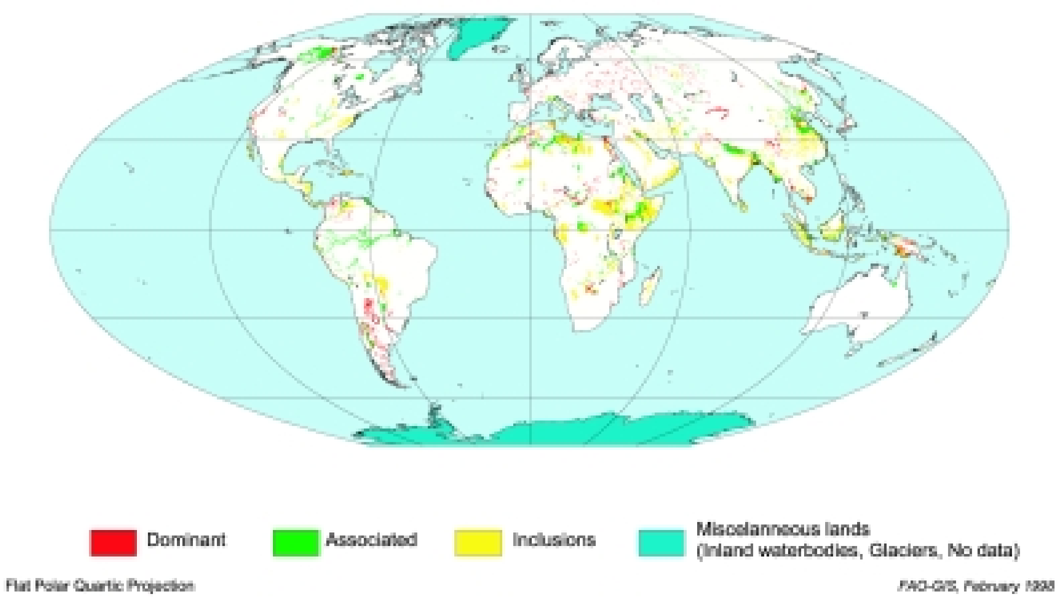
Regional distribution of Fluvisols

Fluvisols occur on all continents and in all climates. They occupy some 350 million hectares worldwide of which more than half are in the tropics. Major concentrations of Fluvisols are found:

1. *along rivers and lakes*, e.g. in the Amazon basin, the Ganges plain of India, the plains near Lake Chad in Central Africa, and the marsh lands of Bolivia and northern Argentina;
2. *in deltaic areas*, e.g. the deltas of the Ganges/Brahmaputra, Indus, Mekong, Mississippi, Nile, Niger, Orinoco, Rio de la Plata, Po, Rhine and Zambesi;
3. *in areas of recent marine deposits*, e.g. the coastal lowlands of Sumatra, Kalimantan and Irian (Indonesia).

Major areas of Thionic Fluvisols (‘*Acid Sulfate Soils*’) occur in the coastal lowlands of southeast Asia (Indonesia, Vietnam, Thailand), West Africa (Senegal, the Gambia, Guinea Bissau, Sierra Leone, Liberia) and along the north-eastern coast of South America (Venezuela, the Guyanas). Figure 1 shows the world-wide distribution of Fluvisols.

Figure 1
Fluvisols world-wide



Associations with other Reference Soil Groups

Fluvisols occur alongside other ‘typical’ soils of aqueous sedimentary environments such as Arenosols, Cambisols, Gleysols and Solonchaks, and also with weakly developed soils such as Leptosols and Regosols.

Genesis of Fluvisols

Fluvisols are young soils that have '*fluvic soil properties*'. For all practical purposes this means that they receive fresh sediment during regular floods (unless the land was empoldered) and (still) *show stratification and/or an irregular organic matter profile*.

Fluvisols in upstream parts of river systems are normally confined to narrow strips of land adjacent to the actual riverbed. In the middle and lower stretches, the flood plain is wider and has the classical arrangement of levees and basins, with coarsely textured Fluvisols on the levees and more finely textured soils in basin areas further away from the river.

In areas with marine sediments, relatively coarse-textured Fluvisols occur on barriers, cheniers, sand flats and crevasse splays; finely textured Fluvisols are found on clayey tidal flats and in chenier plains. Where rivers carry only fine-grained material to the sea, coastal plains (and their Fluvisols) are entirely clayey.

Permanent or seasonal saturation with water preserves the stratified nature of the original deposits but when soil formation sets in, a *cambic* subsurface horizon will quickly form, transforming the Fluvisol into a Cambisol or Gleysol (depending on the water regime).

Genesis of Thionic Fluvisols ('Acid Sulfate Soils')

The only difference between the parent material of Thionic Fluvisols and that of other Fluvisols is the presence of pyrite (FeS_2) in the former.

Formation of pyrite can take place during sedimentation in a marine environment if the following conditions are met:

1. *Iron* must be present. Most coastal sediments contain easily reducible iron oxides or hydroxides.
2. *Sulfur* must be present. Seawater and brackish water contain sulfates.
3. *Anaerobic conditions* must prevail to allow reduction of sulfate and iron oxides. This condition is met in fresh coastal sediments.
4. *Iron- and sulfate-reducing microbes* must be present; these occur in all coastal sediments.
5. *Organic matter* is needed as a source of energy for the microbes; it is present in abundance where there is lush pallustric vegetation (e.g. a mangrove forest, reeds or sedges).
6. *Tidal flushing* must be strong enough to remove the alkalinity formed in the process of pyrite formation.
7. *Sedimentation must be slow.* Otherwise, the time will be too short to form sufficient pyrite for potentially acid sediment.

The mechanism of pyrite accumulation is essentially as follows: Microbes reduce ferric (Fe^{3+}) iron to ferrous (Fe^{2+}) ions, and sulfate (SO_4^{2-}) to sulfide (S^{2-}) under oxygen-poor conditions (i.e. under water). Organic matter is decomposed in the process, ultimately to bicarbonates. Thus, a potentially acid compound (pyrite) and alkaline compounds (bicarbonates) are formed in an initially neutral system. Tidal flushing removes the alkalinity (HCO_3^-), and potentially acid pyrite remains behind.

Pyrite is formed in a number of steps, but the 'overall' reaction equation reads:

$$Fe_2O_3 + 4\ SO_4^{2-} + 8\ CH_2O + 1/2\ O_2 = 2\ FeS_2 + 8\ HCO_3^- + 4\ H_2O \quad (1)$$

Pyrite oxidation:

When pyritic sediment falls dry, oxygen penetrates and pyrite is oxidized, by microbial intervention, to sulfuric acid (H_2SO_4) and ferric hydroxide ($Fe(OH)_3$). Soluble ferrous sulfate ($FeSO_4$) and (meta-stable) '*jarosite*' ($KFe(SO_4)_2(OH)_6$) and/or '*schwertmannite*' ($Fe_{16}O_{16}(SO_4)_3(OH)_{10}.10H_2O$) are intermediate products in this process. Jarosite has a typical straw-yellow colour; schwertmannite is yellowish brown. These minerals are easily recognized in the field and are indicative of 'Actual' Acid Sulfate Soils, i.e. Thionic Fluvisols with a *sulfuric horizon.* 'Potential' Acid Sulfate Soils contain *sulfidic soil material* that contains pyrite but has not oxidized to the extent that the soil-pH dropped to a value below 3.5.

The following reaction equations describe successive steps in pyrite oxidation. The mineral *'jarosite'* will be followed in this text; it is formed at soil-pH < 3.5 if sufficient K^+-ions are present:

$$FeS_2 + 7/2\ O_2 + H_2O = Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+ \qquad (2)$$

In the presence of carbonates, no lowering of the pH takes place even though much acidity is released.

$$CaCO_3 + 2\ H^+ = Ca^{2+} + H_2O + CO_2 \qquad (3)$$

In strongly calcareous soils or in very dry conditions, gypsum may precipitate:

$$Ca^{2+} + SO_4^{2-} + 2\ H_2O = \underset{(\textit{gypsum})}{CaSO_4.2H_2O} \qquad (4)$$

In the absence of carbonates, hydrogen produced is not neutralized and the pH of the sediment falls sharply. The soluble ferrous iron produced according to equation (2) is mobile; it oxidizes to jarosite in places where oxygen is present, i.e. in cracks and along root channels:

$$Fe^{2+} + 2/3\ SO_4^{2-} + 1/3\ K^+ + 1/4\ O_2 + 3/2\ H_2O = 1/3 \text{ jarosite} + H^+ \quad (5)$$

With time, the hydrogen ions are removed from the system by percolation or lateral flushing, and jarosite is hydrolyzed to ferric hydroxide:

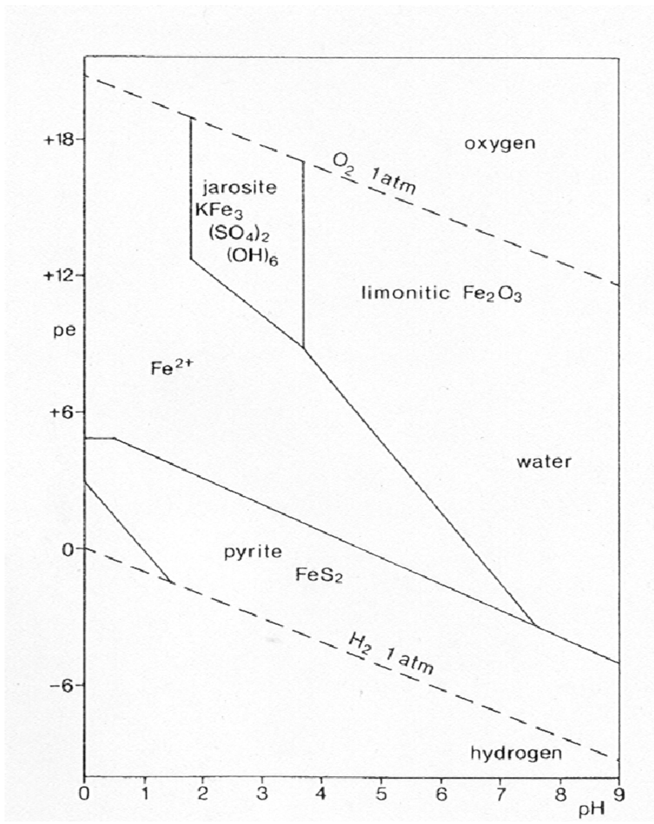
$$1/3 \text{ jarosite} + H_2O = 1/3\ K^+ + Fe(OH)_3 + 2/3\ SO_4^{2-} + H^+ \qquad (6)$$

The (poorly crystallized) ferric hydroxide will eventually transform to *goethite*:

$$Fe(OH)_3 = \underset{(\textit{goethite})}{FeOOH} + H_2O \qquad (7)$$

The stability of the various iron minerals formed in the process of pyrite oxidation is strongly influenced by the redox potential of the soil material (a measure of the quantity of oxygen present) and the soil-pH. Figure 2 presents a diagram of the stability of iron compounds in relation to redox potential (pe) and soil-pH.

Figure 2
pe:pH diagram of pyrite, limonitic Fe_2O_3, jarosite and dissolved K^+, SO_4^{2-}, Fe^{2+} and Fe^{3+} at $\log[SO_4^{2-}] = -2.3$, $\log[K^+] = -3.3$, $\log[Fe^{2+}+Fe^{3+}] = -5$ and 1 atm. total pressure. Source: Miedema, Jongmans & Slager, 1973



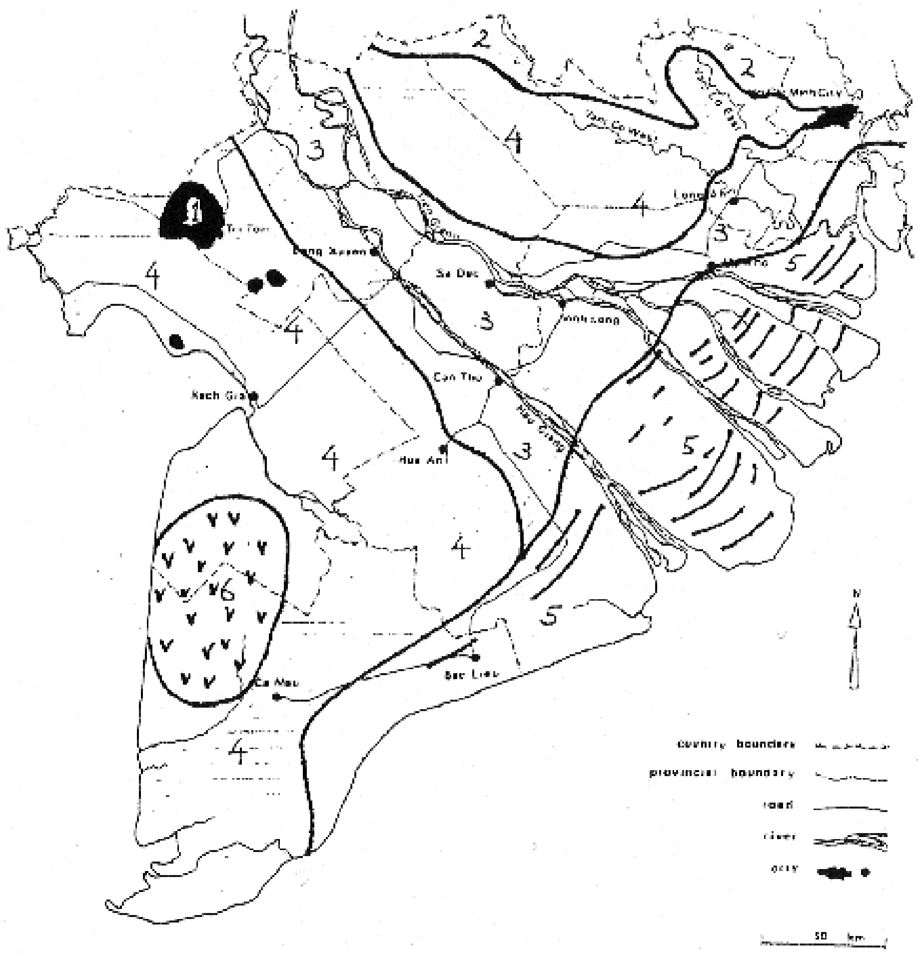
The foregoing shows that aeration of fresh, non-calcareous pyritic sediments, e.g. by forced drainage, results in large quantities of H^+-ions being released to the soil solution. These H^+-ions lower the pH of the soil and exchange with bases at the cation exchange complex. Once the soil-pH has fallen to a level between pH 3 and pH 4, the clay minerals themselves are attacked. Mg, Fe and, in particular, Al are released from the clay lattices, and noxious Al^{3+}ions become dominant in the soil solution and at the exchange complex.

Figure 3 shows the physiographic structure of the Mekong delta in Vietnam. The figure illustrates the relation between physiography and the occurrence of Fluvisols, and of Thionic Fluvisols in particular.

In the Mekong Delta, pyritic sediments are common in the depressions (map unit 4) where extensive areas of Thionic Fluvisols are found. There is no pyrite in the soils of map units 3 (fresh water deposits; no sulphate present during sedimentation), and 5 (sedimentation rate too high). The lower tiers of topogenous deltaic peat (map unit 6) may well contain pyrite.

Note that many soils in river deposits and marine sediments in the Mekong Delta have lost their fluvic soil properties, i.e. they are no longer stratified or have developed a cambic subsurface horizon. Most of these soils key out as Gleysols.

Figure 3
Physiographic sketch map of the Mekong Delta, Vietnam



Legend: (1) Granite hills (2) Pleistocene alluvial terraces (3) Holocene complex of river levees and basins (4) Holocene brackish water sediments in wide depressions (5) Holocene marine sand ridges and clay plains (6) Holocene peat dome.

Characteristics of Fluvisols

Morpholigical characteristics

Fluvisols are very young soils with weak horizon differentiation; they have mostly AC-profiles and are predominantly brown (aerated soils) and/or grey (waterlogged soils) in colour.

Their texture can vary from coarse sand in levee soils to heavy clays in basin areas. Most Fluvisols show mottling indicative of alternating reducing and oxidizing conditions. However, even if *'gleyic colour patterns'* occur in the upper 50 cm of the profile, the soils are not classified as Gleysols because their fluvic properties have priority in the 'Key to Reference Soil Groups'.

It is evident that the characteristics of Fluvisols are dominated by their recent sedimentation and wetness: stratification, beginning ripening, chemical properties influenced by alternate reducing and oxidizing conditions, and in some environments also soil salinity. Rather special are the characteristics of Thionic Fluvisols; they will be discussed in some detail.

Hydrological characteristics

Most Fluvisols are wet in all or part of the profile due to stagnating groundwater and/or flood water from rivers or tides. Terraces are much better drained than the active flood plain; terrace soils are normally well-homogenized and lack fluvic properties.

Physical characteristics

The 'ripening stage' of sedimentary material is judged by sqeezing a lump of soil material through one's fingers and interpreting the resistance felt. Wet clays and silt soils that have lost little water since deposition are soft and 'unripe'. Such soils pose problems for agricultural use; they have a low 'bearing capacity' and machines cannot be used on them.

Many coastal landforms were at one time colonized by pallustric vegetation (e.g. mangroves or reeds) that left large tubular pores in the sediment. Fluvisols on river levees and coastal sand ridges are porous and better drained than soils in low landscape positions.

Chemical characteristics

Most Fluvisols have neutral or near-neutral pH values, which do not impair the availability of nutrients. Most coastal sediments contain some calcium carbonate (seashells !), and the exchange complex is saturated with bases from the sea water. High sodium saturation is not uncommon and high levels of electrolytes in the soil moisture can be a problem as well.

Thionic Fluvisols

The hydrological and physical properties of Thionic Fluvisols are similar to those of other Fluvisols but their chemical characteristics are decidedly different. A distinction must be made between *'Potential Acid Sulfate Soils'*, which are not yet oxidized but contain pyrite in the soil material, and *'Actual Acid Sulfate Soils'*, which are oxidized and acidified.

Unfavourable properties of *Potential Acid Sulfate Soils* are:

1. *Salinity*: Potential Acid Sulfate Soils are mostly situated in coastal areas with tidal influence.
2. *Strong acidification upon drainage*.
3. *Low accessibility/trafficability*: Potential Acid Sulfate Soils have not ripened and consist of soft mud.
4. *High permeability*: root channels of the (natural) pallustric vegetation made many deposits excessively permeable to water.

5. *Flooding* of the land: flooding at spring tide may cause damage to crops.
6. *Engineering problems* arise when dikes, etc are constructed on soft mud. Acidity from oxidizing dike material attacks steel and concrete structures.

Unfavourable properties of *Actual Acid Sulfate Soils* are:

1. *Low soil-pH*: most plants can tolerate pH values as low as pH 4, but only if the supply of nutrients is well balanced.
2. *Aluminium toxicity* can occur at a low soil-pH; generally valid toxicity limits cannot be given as toxicity is co-determined by such factors as 'crop/variety', 'availability of nutrients', 'growth stage of the plants', etc.
3. *Salinity:* salts from seawater can cause high electrolyte levels; in addition, sulphate levels can build up in the soil solution to the extent that the soil is to be regarded saline.
4. *Phosphorus deficiency*: high aluminium levels in the soil solution cause precipitation of insoluble Al-phosphates.
5. *Ferrous iron (Fe^{2+}) toxicity* is a common problem where rice is cultivated on Actual Acid Sulfate Soils. Insoluble ferric iron compounds are oxidized to soluble ferrous iron compounds in flooded rice fields.
6. *Acidification of surface water*: when Actual Acid Sulfate Soils are flooded for rice cultivation, soluble ferrous iron can diffuse to the surface water and be oxidized to ferric iron.

   $$2\ Fe^{2+} + \tfrac{1}{2}\ O_2 + 5\ H_2O = 2\ Fe(OH)_3 + 4\ H^+$$

   This acidifies the surface water and can cause irreparable damage to structures and fish in a very short time.
7. *N-deficiency*: mineralization of organic matter by microbial action is slow in (wet, cold) Actual Acid Sulfate Soils.
8. *Engineering problems*: acidity from surface water attacks steel and concrete structures.
9. *H_2S toxicity* becomes a problem where Actual Acid Sulfate Soils are flooded for long periods (a year or longer). Sulfate will then be reduced to H_2S, which is toxic at very low concentrations.

Management and use of Fluvisols

The good natural fertility of most Fluvisols (young soils!) and attractive dwelling sites on river levees and on higher parts in marine landscapes were recognized already by pre-historic man. Later, great civilizations developed in river landscapes and on marine plains.

Landuse on Fluvisols in the tropics:

Paddy rice cultivation is widespread on tropical Fluvisols with satisfactory irrigation and drainage. Paddy land should be dry for at least a few weeks every year, to prevent the soil's redox potential from becoming so low that nutritional problems (iron, H_2S) arise. A dry period also stimulates microbial activity and promotes mineralization of organic matter. Many dryland crops are grown on Fluvisols, normally with some form of artificial water control.

Tidal lands that are strongly saline are best kept under mangroves or other salt tolerant vegetation. Such areas are ecologically valuable and can be used (with caution!) for fishing, hunting, salt pans, or woodcutting for charcoal or firewood.

There are two (opposite) strategies thinkable for 'reclaiming' and using *Potential Acid Sulfate Soils*:

1. The first strategy is to *drain and completely oxidize the soil, and then flush the acidity* formed out of the soil. Leaching can initially be done with saline or brackish water; this will not only remove soluble acidity, but also expel undesirable aluminium ions from the exchange complex. This strategy solves the problem for once and for all but has severe disadvantages: it is expensive, poses a threat to the environment (acid drain water!) and depletes the soil of useful elements together with the undesirable ones. The method has been applied with some success in coastal rice growing areas in Sierra Leone and in areas with fishponds in the Philippines. It proved disastrous in Senegal, where insufficient water was available for leaching, and in the Netherlands where the first generation of settlers barely survived the construction of the Haarlemmermeer polder. Liming of drainage water has been applied to reclaim Acid Sulfate soils in Australia.
2. The second strategy is to try to *limit pyrite oxidation by maintaining a high groundwater table.* A precondition is the availability of sufficient water. This method also requires substantial investments in water management, while the potential danger of acidification remains present. This strategy is widely followed, both in temperate regions and in the tropics, often with ingenious adaptations to suit local conditions and practices.

When discussing management and use of Actual Acid Sulfate Soils, a distinction must be made between areas with shallow inundation (less than 60 cm) and areas with deep inundation. Flap gates can be used for water control in areas with shallow inundation and at least some tidal influence in creeks or canals. In the rainy season, water can be discharged at low tide, or irrigation water can be applied as needed. Where tide water is fresh water, spring tides can be used for irrigation in the dry season. Where tides are not high enough to flood the land for rice cultivation, dry crops can be grown using flap gates to maintain a shallow groundwater table.

In many coastal lowlands, the *'intensive shallow drainage system'* is practiced: shallow ditches are dug at narrow spacings. This system relies on sufficient leaching of the surface soil at the start of the rainy season. Dryland crops can only be grown on raised beds whereby care must be taken not to turn the profile upside down and bring the most acid part (the subsurface soil) to the top. Rice is grown in the shallow depressions between the raised beds.

Table 1 presents theoretical lime requirements for complete neutralization of soils with various contents of oxidizable sulphur. The neutralizing capacity of a 10 cm layer (without lime; neutralization by exchange ions only) is also given. The table demonstrates the practical impossibility of the liming option: very few farmers can afford to apply to an average Acid Sulfate Soil (say 1.5 percent sulfur and an apparent density of 1.0 Mg/m^3) a total of 28 (i.e. 47 minus 19) tons of lime per hectare. And that covers only the needs of the top 10-cm layer, assuming that no new acid forms during a subsequent dry spell.

TABLE 1
Lime requirements for complete neutralization of a 10-cm soil layer. After Dent & Raiswell, 1982

	Lime requirement of a 10 cm layer, in tons of lime/ha						Neutralizing capacity of the 10 cm layer, (no lime present) in clayey soil
Apparent soil density (Mg/m^3)	percent oxidizable sulfur 0.5	1	1.5	2	3	4	
0.6	9	19	28	37	56	74	11
0.8	12	25	37	50	74	112	14
1.0	16	31	47	62			19
1.2	19	37	56	74			22

Many lands with Actual Acid Sulfate Soils are not used for agriculture at all. Such hostile 'wet desert' lands have an adapted vegetation, a limited fauna, and acid surface water, especially early in the wet season when acid substances dissolve. The situation seems to be a little less bleak in the equatorial climatic zone than in monsoon climates. There, Acid Sulfate Soils will not dry out as easily as in the monsoon area, and more water is available for management measures throughout the year.

GLEYSOLS (GL)

The Reference Soil Group of the Gleysols holds wetland soils that, unless drained, are saturated with groundwater for long enough periods to develop a characteristic "gleyic colour pattern". This pattern is essentially made up of reddish, brownish or yellowish colours at ped surfaces and/or in the upper soil layer(s), in combination with greyish/bluish colours inside the peds and/or deeper in the soil. Common international names are 'Gleyzems' and 'meadow soils' (Russia), 'Aqu-' suborders of Entisols, Inceptisols and Mollisols (USA), 'Gley' (Germany), and 'groundwater soils' and 'hydro-morphic soils'.

Definition of Gleysols[#]

Soils,

1. having *gleyic*[@] properties within 50 cm from the soil surface; and
2. having no diagnostic horizons other than an *anthraquic*[@], *histic*[@], *mollic*[@], *ochric*[@], *takyric*[@], *umbric*[@], *andic*[@], *calcic*[@], *cambic*[@], *gypsic*[@], *plinthic*[@], *salic*[@], *sulfuric*[@] or *vitric*[@] horizon within 100 cm from the soil surface.
3. having no *abrupt textural change*[@] within 100 cm from the surface.

Common soil units:

Thionic*, Histic*, Gelic*, Anthraquic*, Vertic*, Endosalic*, Andic*, Vitric*, Plinthic*, Mollic*, Gypsic*, Calcic*, Umbric*, Arenic*, Tephric*, Stagnic Tephric*, Abruptic*, Humic*, Calcaric*, Takyric*, Alcalic*, Toxic*, Sodic*, Alumic*, Dystric*, Eutric*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups

[@] Diagnostic horizon, property or material; see Annex 2 for full definition.

[*] Qualifiers for naming soil units; see Annex 3 for full definition.

Summary description of Gleysols

Connotation: soils with clear signs of excess wetness; from R. *gley*, mucky mass.

Parent material: a wide range of unconsolidated materials, mainly fluvial, marine and lacustrine sediments of Pleistocene or Holocene age, with basic to acidic mineralogy.

Environment: depression areas and low landscape positions with *shallow groundwater*.

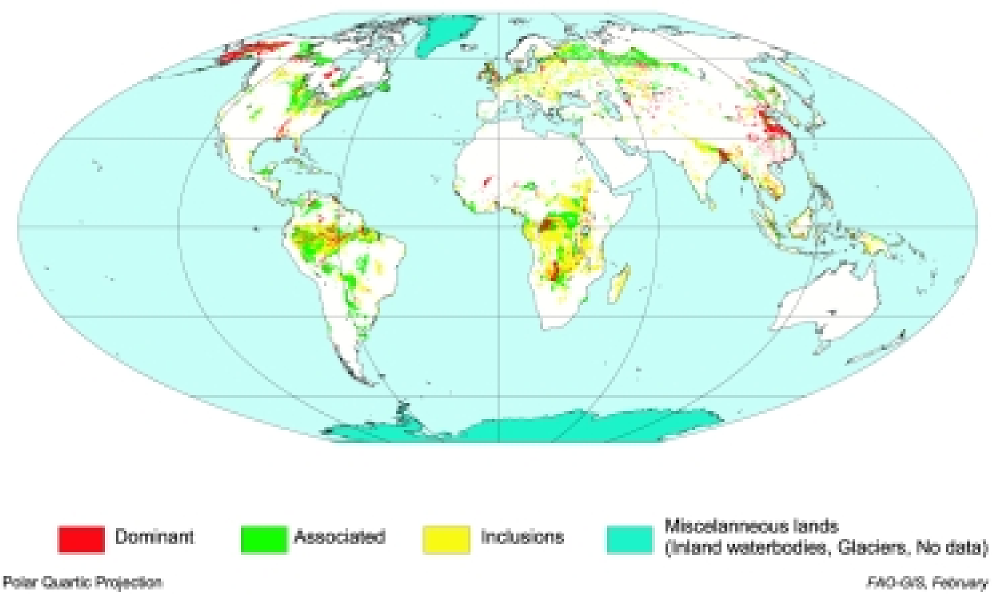
Profile development: mostly A(Bg)Cr or H(Bg)Cr profiles. Evidence of reduction processes with or without segregation of iron compounds within 50 cm of the surface.

Use: wetness is the main limitation of virgin Gleysols; these are covered with natural swamp vegetation and lie idle or are used for extensive grazing. Artificially drained Gleysols are used for arable cropping, dairy farming and horticulture. Gleysols in the tropics and subtropics are widely planted to rice.

Regional distribution of Gleysols

Gleysols occupy an estimated 720 million hectares world-wide. They are azonal soils and occur in nearly all climates, from perhumid to arid. The largest extent of Gleysols is in sub-arctic areas in northern Russia, Siberia, Canada and Alaska, and in humid temperate and subtropical lowlands, e.g. in China and Bangladesh. An estimated 200 million hectares of Gleysols are found in the tropics, mainly in the Amazon region, equatorial Africa and the coastal swamps of Southeast Asia. See Figure 1.

Figure 1
Gleysols world-wide



Associations with other Reference Soil Groups

Gleysols of the sub-arctic and temperate latitudes are associated with *Histosols* and with *Fluvisols* (in riverine and coastal areas). Gleysols at higher landscape positions are confined to depression areas with shallow groundwater where they occur adjacent to *Luvisols* and *Cambisols*. Gleysols in the steppe zone are found together with *Chernozems* and *Phaeozems*. Gleysols in arid regions occur predominantly in fluvial and marine lowlands, e.g. together with *Solonchaks* and *Solonetz*. A wide variety of soils (*inter alia* Calcisols, Gypsisols, Cambisols, Regosols, Arenosols and Leptosols) can be expected on adjacent uplands.

Gleysols in the humid tropics are confined to structural wetlands; *Acrisols, Lixisols, Nitisols, Alisols* and *Ferralsols* occur in (better-drained) adjacent uplands.

Genesis of Gleysols

The formation of Gleysols is conditioned by excessive wetness at shallow depth (less than 50 cm from the soil surface) in some period of the year or throughout the year. Low-redox conditions, brought about by prolonged saturation of soil material in the presence of organic matter, cause reduction of ferric iron compounds to (mobile!) ferrous compounds. This explains why the permanently saturated subsoil layers of Gleysols have neutral whitish/greyish or bluish to greenish matrix colours: with the iron compounds mobilized and removed, the soil material shows its own colour, normally with a Munsell hue notation that is less red than 2.5Y.

Note that reduction of oxides to soluble Fe^{2+} and/or Mn^{2+} compounds will in practice only take place if the soil is periodically saturated with water that contains the dissolved products of organic matter decomposition.

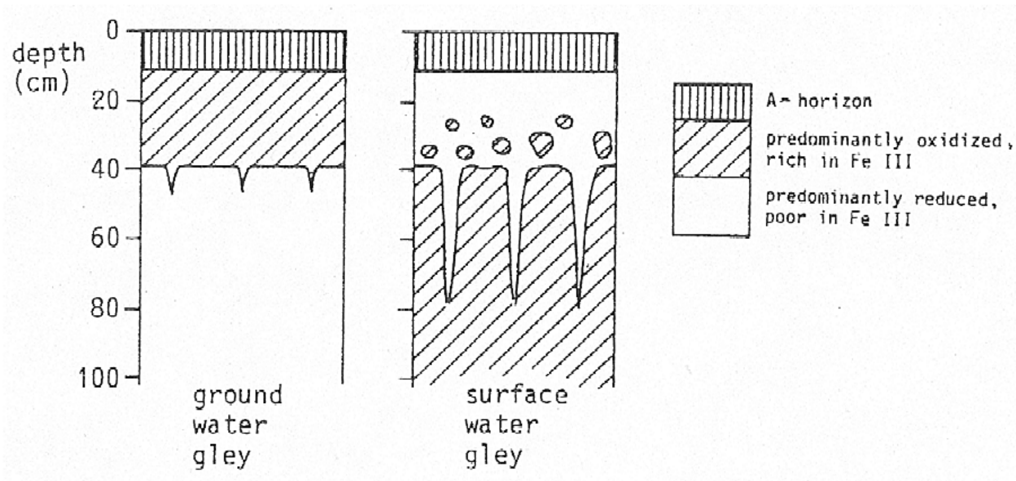
Subsequent oxidation of transported Fe^{2+} and/or Mn^{2+} compounds (back) to oxides can take place near fissures or cracks in the soil, along living roots that have *'aerenchym'* (air ducts, e.g. in the roots of paddy) and along former root channels where there is supply of oxygen. Hysteresis between oxidation and (slower) reduction processes results in net accumulation of oxides near aerated spots. The soil develops a characteristic '*gleyic colour pattern*', with '*redoximorphic features'*. These comprise '*reductomorphic*' and '*oximorphic*' properties.

- *Reductomorphic properties* signify permanently wet conditions. They are expressed by neutral whitish/greyish or bluish and greenish *'gley colours'* in more than 95 percent of the soil matrix. Near the capillary fringe, the (subsoil) layer with reductomorphic properties may include up to 5 percent oxidation colours, e.g. as mottles (around air pockets) or 'root prints' (former root holes lined with iron oxide).
- *Oximorphic properties* indicate alternating reducing and oxidizing conditions, as occur near the capillary fringe and in the surface layers of soils with fluctuating groundwater depth. Oximorphic properties are expressed by reddish brown or bright yellowish brown mottles on aggregate surfaces and on walls of pores. Acid sulphate soils feature bright yellow mottles of *jarosite* (at pH < 3.5) or *schwertmannite* (at pH 3.0-4.5).

Note that '*gleyic properties*' are strictly associated with movement of the *groundwater table*; mottled, oxidized horizons occur on top of a fully *reduced* subsoil. A different type of mottling is found where perched water occurs on top of a slowly permeable subsurface horizon while the real groundwater table occurs at greater depth. In this case, the reduced horizon overlies an *oxidized* subsurface horizon. (Figure 2). This configuration occurs in soils that have '*stagnic properties*' and show a '*stagnic colour pattern*'.

The stagnic colour pattern differs from the gleyic colour pattern in that surfaces of peds (or parts of the soil matrix) are lighter and paler, and the interior of peds (or parts of the soil matrix) are more reddish and brighter than the (mixed average of the) non-redoximorphic soil material of the layer. The stagnic colour pattern may occur directly below the surface horizon or plough layer, or below an albic horizon.

Figure 2
Schematic horizon configurations of soils with *gleyic properties* and soils with *stagnic properties*



The soils of rice paddies

The soils of rice paddies may be true Gleysols but are more often Anthraquic soil units in some other Reference Soil Group. By and large, there are two broad categories of 'paddy soil':

1. *paddy soils in wetlands*, e.g. Gleysols and Fluvisols (with a completely reduced subsoil), and
2. *anthraquic* paddy soils formed in originally well-drained land.

Repetitive puddling of the surface soil of paddy soils has produced a thin, compacted and slowly permeable plough sole at the depth of cultivation. Most Anthraquic Gleysols have a reddish brown to black accumulation horizon of iron and/or manganese oxides at some depth below the plough sole. This accumulation layer formed as a result of intensive reduction processes in the puddled surface layer and translocation and precipitation of iron and manganese compounds in the (oxidized) subsoil. The accumulation layer may indurate to an impenetrable hardpan.

Characteristics of Gleysols

Morphological characteristics

Soil morphological features are valuable indicators of a soil's water regime but correct interpretation of such features is not always easy.

- A soil may be saturated with water and have a low redox potential but not show any redoximorphic features because very stable iron minerals such as coarse-grained hematite did not dissolve.
- Redoximorphic features may also be absent if water-saturation occurs under extremely cold conditions, in chemically poor environments with little or no organic matter, or by rapidly passing oxygen-rich water.

Interpretation of oximorphic features is further complicated by the possibility that the features may be 'fossil'. Soils, which were water-saturated and reduced in early Holocene or in Pleistocene times, may still show the signs today, even though they now have an entirely different water regime. The same may happen where soils are artificially drained.

Gleysol profiles have normally a spongy or matted litter layer resting on a dark grey Ah-horizon that changes sharply into a mottled grey or olive Bg-horizon. With depth, the Bg-horizon grades into a grey, olive or blue anaerobic Cr-horizon. Gleysols in fluvi-glacial sands in Central Europe may contain accumulations of hardened *'bog iron'* (smelted by Iron Age man).

Gleysols of the savannas have normally very dark grey to black, heavy clay surface layers that continue down to 2 metres or more in some profiles but give place to pale grey subsurface soil with prominent mottling in others (Fitzpatrick, 1986). The soil structure is medium blocky or even crumb near the soil surface but becomes coarsely prismatic at some depth. The soil material is hard when dry and sticky when wet.

Where Gleysols remain waterlogged throughout the year, except perhaps for short periods, the topsoil is typically a mixed organic and mineral (muck) H-horizon. It tops a mottled clay or sandy clay subsurface horizon over permanently anaerobic subsoil.

Mineralogical characteristics

Reddish brown (*ferrihydrite*) or bright yellowish brown (*goethite*) mottles are indicators of *oximorphic properties*. Reductomorphic properties are not evidenced by specific minerals but rather by absence of iron (hydr)oxides and by 'neutral whitish/greyish or bluish to greenish' matrix colours. Gleysols of coastal areas with salt meadows may feature 'blue-green rust', i.e. the interior of structural peds is coloured greenish by Fe^{2+}/Fe^{3+} -oxides.

Hydrological characteristics

The dominant attribute of Gleysols is prolonged saturation with water, associated with lack of aeration, poor rooting conditions for most crops and poor conditions for soil fauna.

Physical characteristics

Repeated wetting and drying may cause soil densification due to weakening of interparticle bonds during saturation and contraction of soil particles upon desaturation. The soil structure is likely to deteriorate if too wet a soil is tilled. Trafficability is a problem with many Gleysols.

Chemical characteristics

Gleysols in depressions or at the lower ends of slopes are generally considered to be 'comparatively fertile' because of their fine soil texture, slow rate of organic matter decomposition and influx of ions from adjacent uplands. They have more organic matter, greater cation exchange capacity, higher base saturation, and usually also higher levels of phosphorus and potassium, than adjacent upland soils.

Management and use of Gleysols

The main obstacle to utilisation of Gleysols is the necessity to install a drainage system, designed to either lower the groundwater table, or intercept seepage or surface runoff water. Adequately drained Gleysols can be used for arable cropping, dairy farming or horticulture.

Soil structure will be destroyed for a long time if (too) wet soils are tilled. Gleysols in (depression) areas with unsatisfactory drainage possibilities are therefore best kept under permanent grass cover or (swamp) forest. Liming of drained Gleysols that are high in organic matter and/or of low pH value creates a better habitat for micro- and meso-organisms and enhances the rate of soil organic matter decomposition (and the supply of plant nutrients).

Gleysols can be put under tree crops only after the water table has been lowered with deep drainage ditches. Alternatively, the trees are planted on ridges that alternate with shallow depressions. In the 'sorjan' system that is widely applied in tidal swamp areas with pyritic sediments in Southeast Asia, rice is grown in the inundated depressions between ridges. The difficulties discussed for Thionic Fluvisols apply also to Thionic Gleysols (see under Fluvisols).

Major landforms in mountains and formerly glaciated regions

Unstable rocky slopes and outcrops of bedrock are common features in mountainous and (formerly) glaciated regions, notably in

1. '*High mountain areas*' that lost any old soil cover (scraped off by ice!) during the latest glacial advances. This category includes almost all mountain chains in the Temperate Zone (Alps, Rocky Mountains) and much of the tropical high mountain belts above the limit of Pleistocene glaciation, i.e. above 3000 m near the equator (Andes and Himalayas).
2. '*Low-range mountains*' (Caledonian and Hercynian orogenesis), mainly in the Temperate Zone. These regions were not or only slightly glaciated in the recent geological past, but suffered so much periglacial slope action that they possess extremely stony soils.
3. '*(Formerly glaciated) shields*' such as Scandinavia and northern Canada, which were subject to glaciation and consist predominantly of solid rock (scraped clean) or of stony moraine deposits.

Landforms in high mountain areas

The highest mountains in the world are all relatively young; they started to form in the Oligocene during the period of '*Alpine orogenesis*' and belong to mountain belts situated at plate boundaries. Repeated levelling measurements indicate that these mountains are still actively forming today. Their properties depend in part on the nature of the plate boundaries. There are three basic plate-boundary types:

1. *'Island arcs'* (a curved array of volcanic islands) form where one oceanic plate is being subducted below another. In the early stages of subduction, the islands are almost entirely volcanic; examples of such islands are the Lesser Antilles, and the Aleutian Islands off Alaska. Later, the islands acquired a more complex geological structure such as Japan and the Philippines. Volcanism is initially basaltic to andesitic and becomes increasingly andesitic later on.
2. *'Cordilleran mountains'* form where oceanic crust is being subducted below a continental plate. The Andes and the American Cordilleras are examples of this type. Andesitic volcanism is prominent in cordilleran mountains. Folded sedimentary rocks, igneous intrusions (granite, granodiorite), and older metamorphic rocks from all geologic periods can be found in these mountain belts.
3. *'Continent-continent collision mountains'* differ from the preceding types in that volcanism has now become much less prominent. Compression is much stronger than in cordilleran belts, so that *'nappes'* (low-angle overthrust sheets that may have been displaced hundreds of kilometres from their original position) are common. In every other respect, they resemble the cordilleran belts and a similar array of igneous, sedimentary and metamorphic rocks of greatly differing ages can be found. Examples of continent-continent collision mountains are the Alps and their continuation into Eastern Europe, Iran and the Himalayas. Mountain building is still going on in these areas; the Caucasus, for instance, is still being uplifted at a rate of 2 cm per year.

Rock outcrops and shallow, stony weathering mantles are prominent in all three mountain types, especially in the zone between the actual snow line and the lowermost extension of the ice during the last glaciation. (The present glaciers and snowfields are not considered here.) Typical erosion phenomena of this zone are the *'cirques'* (amphitheatre-like former snow-accumulation basins) and *'U-shaped trough valleys'*, former fluvial valleys modified by glacial abrasion. Both have steep upper slopes, usually consisting of rough rock outcrops, and extensive lower slopes of rock debris. The sizes of rock fragments vary with the lithology: highly fissile rocks such as shale, schist and dolomite disintegrate to fine debris whereas granites give huge angular boulders.

The High Mountain Zone contains soil parent materials of glacial, fluvio-glacial and lacustrine origin alongside rock outcrops and in-situ rock weathering products:

1. *'Glacial deposits'* consist of unsorted, boulder and clay-rich *'glacial till'* formed at the base of valley glaciers. *'Moraines'* of unsorted, and usually clay-poor material mark the end and/or sides of valley glaciers.
2. *'Fluvio-glacial deposits'* are meltwater deposits of sorted sand and gravel similar to the deposits of (other) braided rivers.
3. *'Lacustrine deposits'* formed in temporary lakes near the margins of retreating glaciers; they are stratified as a result of seasonal variations in sediment influx (*'varves'*).

Soil formation in these materials is slow (high altitude, low temperature) and has gone on for only 10,000 years or less. Steep slopes are subject to strong erosion, especially if stabilising vegetation is absent. Soils are regularly truncated and in a constant process of rejuvenation. As a result, (poorly developed) Leptosols and Regosols are strongly represented in high mountain areas.

The zone below the Pleistocene glaciation limit contains older weathering profiles, with more developed soils than occur in higher, more recently de-glaciated regions. They will be discussed later when Alpine fold belts lower than 3000 m. are discussed. Volcanic rocks and ash deposits can be widespread in high-mountain regions; volcanic regions and soils developed in volcanic materials are discussed elsewhere in these notes.

Landforms in low-range mountains

The 'low-range mountains' of Central Europe and eastern North America are relicts of gigantic ancient continental collision structures. They formed before the Atlantic Ocean evolved and are attributed to one orogeny that produced the *'Caledonian and Hercynian massifs'*. They extend from northern Norway to Mauritania in N. Africa and from eastern Greenland to the southern USA. Their folded sedimentary and metamorphic rocks indicate a complex orogenic history. Both massifs have an inner zone of crystalline rocks, and an outer zone of low-grade metamorphic and sedimentary rocks. Typical inner-zone, high-grade metamorphic provinces are the Piedmont province of the USA, Brittany, the Central Massif, and the Vosges in France, the Black Forest of Germany and the Bohemian Massifs in central Europe. The Valley-and-Ridge province in the USA, the Ardennes (Belgium), the Rheinische Schiefergebirge (Germany) and Devonshire (U.K.) are largely made up of low-grade metamorphic and sedimentary rocks.

Palaeozoic orogenesis ended approximately 250 million years ago and most Caledonian and Hercynian Massifs have since degraded to low peneplains, e.g. in Brittany (France). In many areas peneplain formation went on until the Tertiary; relic (sub)tropical soils on some (high and flat) peneplain remnants still testify to the occurrence of warmer climates in the past.

The almost flat peneplains and the Mesozoic basins between them (e.g. the Paris and London Basins) were uplifted during the Late Tertiary (Alpine orogeny) and became subsequently incised by rivers. Present day differences in elevation are caused by:

1. *Differential weathering* of rocks of different hardness: hard limestone, dolomite and sandstone formations stand out as ridges in the landscape (*'cuestas'* or *'hogbacks'*); soft shales and marls were eroded away and left gently sloping valleys. Granite intrusions became exposed as *'inselbergs'* (dome-shaped bare granite hills) and *'tors'* (huge heaps of boulders) after the sandy saprolite was washed away from the still unweathered core. Slope processes under (peri)glacial conditions smoothed much of this structural relief during the Ice Ages.
2. *Uplift and renewed incision* of already present ('antecedent') rivers in the low-range Massifs during Alpine orogeny. The larger rivers formed entrenched meanders; today, only a very small river might be present that seems unable to have carved out such a large and deep valley (a so-called *'misfit river'*). Entrenched meanders are common in all Hercynian massifs, both in the USA and in Europe.

The Caledonian mountain ranges of western Norway, Scotland and Ireland were strongly modified by glacial action. Glaciers protruding from the Scandinavian ice-sheet carved out deep valleys, which were later inundated as the sea level rose. The 'fjords' of Norway are exceptionally deep: 1300 m, more than 1 km below the continental shelf. The Hercynian massifs in central Europe were hardly affected by glacial action because they remained below the snowline. However they became exposed to harsh *periglacial* conditions: there is ample evidence of 'frost shattering', 'frost heaving', 'periglacial slope processes' and one finds indications of repeated thawing and freezing of surface soil on top of 'permafrost' subsoil. All these processes promote mixing of soil material with fresh rock fragments from deeper strata, so that many soils became very stony. Remnants of Tertiary regoliths can still be found underneath periglacially affected surface tiers.

Rock outcrops are rare in plateau areas with sedimentary and low-grade metamorphic rocks. But they are common on the steep slopes of rejuvenated valleys. Leptosols and Regosols are the dominant soil groups there.

Landforms on (formerly) glaciated shields

Glaciated shields such as the (Precambrian) Baltic and Canadian Shields are very complex structures; they consist of various high-grade metamorphic rocks and were strongly levelled/abraded in the past. Considering their old age, their present landforms are actually very recent; they were strongly influenced by Pleistocene glaciation. *Till plains*, end- and side-*moraines* and *fluvio-glacial deposits* are very common, as in glaciated mountain areas. Typical landforms such as *'drumlins'*, '*kames*' and *'eskers'* were formed during phases of retreat, standstill and re-advance of the Pleistocene ice sheets. Glaciers or ice sheets became overridden and pushed upward depositing their '*till*' in elongate, elliptic hills.

Recall that *'kames'* and *'eskers'* are fluvio-glacial deposits. Streams carrying meltwater and depositing sediment on top of valley glaciers form kames whereas similar streams running beneath stagnant ice sheets form eskers. When an ice-sheet melts, any coarse sand and gravel will stay behind to form unstable terraces (kames) or well-founded long ridges (eskers) in the landscape.

In places, moving ice scraped off any saprolite that was already present in the landscape. Fresh rock outcrops and *'roches moutonnées'* are common, and relief became subdued. Many streams and (over-deepened) river valleys have orientations that indicate the flow direction of a former ice-sheet or glacier. The last glaciation ended only 10,000 years ago and soils are therefore recent and immature. Cryosols, Leptosols and Regosols are common soils in previously glaciated areas.

LEPTOSOLS (LP)

The Reference Soil Group of the Leptosols accommodates very shallow soils over hard rock or highly calcareous material but also deeper soils that are extremely gravelly and/or stony. Leptosols are azonal soils with an incomplete solum and/or without clearly expressed morphological features. They are particularly common in mountain regions. Leptosols correlate with the 'Lithosols' taxa of many international classification systems (USA, FAO) and with 'Lithic' subgroups of other soils groupings. In many systems, Leptosols on calcareous rock are denoted 'Rendzinas'; those on acid rock are also called 'Rankers'.

Definition of Leptosols[#]

Soils having
1. *continuous hard rock*[@] within 25 cm from the soil surface; or a *mollic*[@] horizon with a thickness between 10 and 25 cm directly overlying material with a calcium carbonate equivalent of more than 40 percent, or less than 10 percent (by weight) fine earth from the soil surface down to a depth of 75 cm; and
2. no diagnostic horizons other than a *mollic*[@], *ochric*[@], *umbric*[@], or *yermic*[@] horizon.

*Common soil units***:**
Lithic*, Hyperskeletic*, Rendzic*, Gelic*, Vertic*, Gleyic*, Mollic*, Umbric*, Humic*, Aridic*, Gypsiric*, Calcaric*, Yermic*, Dystric*, Eutric*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifiers for naming soil units; see Annex 3 for full definition.

Summary description of Leptosols

Connotation: shallow soils; from Gr. *leptos*, thin.

Parent material: various kinds of rock or unconsolidated materials with less than 10 percent fine earth.

Environment: mostly land at high or medium altitude and with strongly dissected topography. Leptosols are found in all climatic zones, particularly in strongly eroding areas.

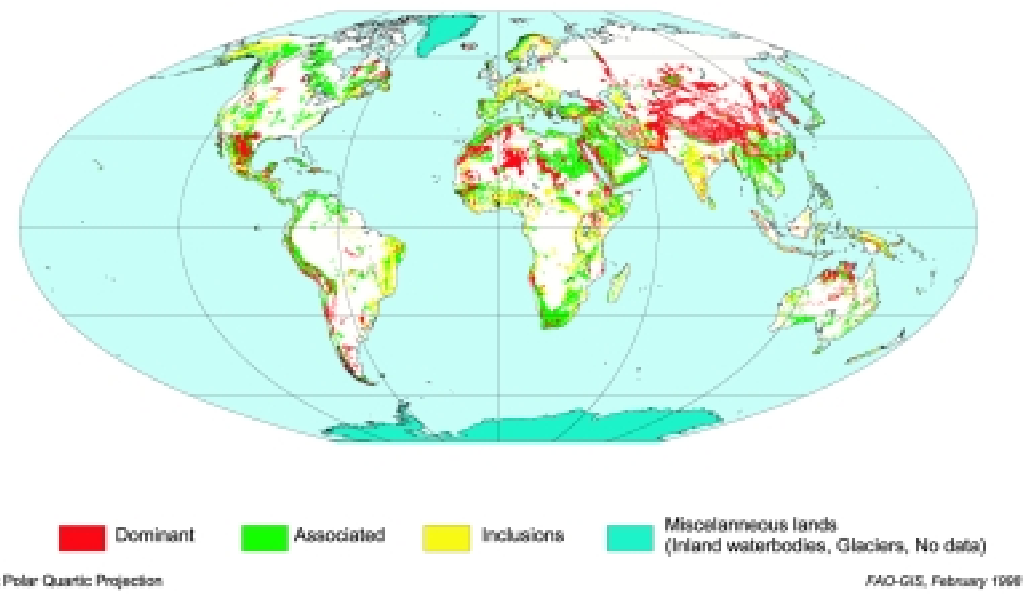
Profile development: A(B)R or A(B)C profiles with a thin A-horizon. Many Leptosols in calcareous weathering material have a mollic A-horizon that shows signs of intensive biological activity.

Use: unattractive soils for arable cropping; limited potential for tree crop production or extensive grazing. By and large, Leptosols are best kept under forest.

Regional distribution of Leptosols

Leptosols are the most extensive Reference Soil Group on earth, extending over approximately 1655 million hectares. Leptosols are found from the tropics to the cold polar regions and from sea level to the highest mountains. Leptosols are particularly widespread in mountain areas, notably in Asia and South America, in the Saharan and Arabian deserts, the Ungava peninsula of northern Canada and in the Alaskan Mountains. Elsewhere, Leptosols can be found on hard rocks or where erosion has kept pace with soil formation or removed the top of the soil profile. Lithic Leptosols (less than 10 cm deep) in mountain regions are the most extensive Leptosols. See Figure 1.

Figure 1
Leptosols world-wide



Associations with other Reference Soil Groups

The WRB definition of Leptosols refers specifically to shallow soils with continuous hard rock within 25 cm from the soil surface, excluding cemented layers such as a *petrocalcic* or *petroplinthic* horizon. However, the definition includes also deeper soils, provided that these have less than 10 percent fine earth over a depth of at least 75 cm. When discussing linkages between (diverse!) Leptosols and other Reference Soil Groups, one might make a distinction between Leptic soil units of other Reference Soil Groups and soil units of Leptosols.

Leptic units of other Reference Soil Groups

The qualifier "Leptic" indicates continuous hard rock between 25 and 100 cm from the soil surface and is listed for many Reference Soil Groups but *not* for Histosols, Anthrosols, Vertisols, Fluvisols, Solonchaks, Gleysols, Podzols, Plinthosols, Ferralsols, Solonetz, Planosols, Chernozems, Kastanozems, Albeluvisols, Alisols, Nitisols and Arenosols.

Leptic units of Histosols, Vertisols and Podzols are known to exist and are likely to be included in the listing in the near future. Leptic units of Fluvisols, Solonchaks, Gleysols, Plinthosols, Ferralsols, Solonetz, Planosols, Chernozems, Kastanozems, Albeluvisols, Alisols and Nitisols are probably rare (or have not been sufficiently documented) or unlikely to occur; some of these may yet have to be included. Leptic Arenosols are excluded because continuous hard rock between 50 to 100 cm is not allowed in Arenosols; soils with a texture of sand or loamy sand above continuous hard rock between 25 and 100 cm would be Areni-Leptic Regosols.

Leptosol soil units

Qualifiers distinguished for the Leptosol reference group link Leptosols to Cryosols (Gelic Leptosols), Gleysols (Gleyic Leptosols), Umbrisols (Umbric Leptosols), Phaeozems (Mollic Leptosols), Regosols (Hyperskeletic Leptosols) and Gypsisols (Gypsiric Leptosols). Because the central concept of Leptosols is one of weakly developed and/or very shallow soils, Leptosols are not supposed to have a histic, andic, spodic, argic or cambic horizon. For the same reason, soils with a petrocalcic, petrogypsic, petroduric or petroplinthic horizon within 25 cm of the surface are not classified as Leptosols but as Calcisols, Gypsisols, Durisols and Plinthosols respectively. Pedogenetic differentiation may still develop in very shallow soils. Thin histic surface layers occur over hard rock, especially in the boreal regions of the world and in areas with high precipitation (e.g. the "blanket peats" of the British Isles). If less than 10 cm thick, the shallow peat layer is ignored and the soils are classified as Lithic Leptosols; if more than 10 cm of peat are present, they key out as (Leptic) Histosols.

The first evidence of pedological development normally hints at formation of a *cambic* subsurface horizon. However, the soil ceases to be a Leptosol and becomes (classified as) a Cambisol as soon as the developing horizon meets all criteria for a real cambic horizon (at least 15 cm thick and its base deeper than 25 cm below the surface).

An andic horizon is not permitted in Leptosols but soils consisting of tephric soil material with less than 10 percent of fine earth represent intergrades of Leptosols to the Andosols.

The definition of the spodic horizon leaves the possibility open that a full-fledged Podzol exists within the depth limits of Leptosols. Such (mature!) soils are not Leptosols, despite the presence of hard rock within 25 cm from the surface, but are classified as (Leptic) Podzols.

The definition of the argic horizon precludes that an argic horizon can be present within the depth limits of Leptosols, unless there is an abrupt textural transition from the overlying horizon to the (more than 7.5 cm thick) argic horizon. In that case the soil is classified as a (Leptic) Luvisol (or Acrisol or Lixisol, depending on CEC_{clay} and base saturation).

"Gleyic properties" in Leptosols are exclusive to (deeper) soils that qualify as Leptosols because they have less than 10 percent (by weight) fine earth to a depth of at least 75 cm. "Stagnic properties" may have to be considered both in Leptosols with continuous hard rock within 25 cm of the surface and in Leptosols with less than 10 percent of fine earth to a depth of 75 cm, but Leptosols with stagnic properties have not been sufficiently documented so far.

Genesis of Leptosols

Leptosols are genetically young soils and evidence of soil formation is normally limited to a thin A-horizon over an incipient B-horizon or directly over the unaltered parent material. The principal soil forming process in Rendzic and Mollic Leptosols is the dissolution and subsequent removal of carbonates. A relatively small residue remains behind and is thoroughly mixed with stable humifying organic matter and, in Rendzic Leptosols, fragments of limestone rock. Swelling and shrinking smectitic clays in the mineral residue are accountable for the dominance of blocky structures. Umbric Leptosols occur mostly on siliceous parent rock in (mountain) regions with a cool climate and a high precipitation sum.

Characteristics of Leptosols

Morphological characteristics

Most Leptosols have an A(B)R or A(B)C configuration of only weakly expressed horizons. Rendzic and Mollic Leptosols have more pronounced morphological features. Their dark brown or black calcareous organo-mineral surface soil, in Rendzic Leptosols speckled with white limestone fragments, has a stable crumb or granular structure, or a vermicular structure with abundant earth worm casts. At the base of the soil profile, there is an abrupt change to the underlying rock or there may be a narrow transition horizon.

Hydrological, chemical and physical characteristics

The Reference Soil Group of the Leptosols includes a wide variety of soils with greatly differing chemical and physical properties. By and large, Leptosols are free-draining soils with the exception of certain Hyperskeletic Leptosols that may have groundwater at shallow depth. Stagnic properties can occur in Leptosols on gentle slopes or in pockets but are rather exceptional.

The physical, chemical and biological properties of non-calcareous Leptosols are largely conditioned by the characteristics of the parent material and the climate. Calcareous Leptosols have generally better physical and chemical properties than non-calcareous ones and are also less diverse. Leptosols are normally free from noxious levels of soluble salts. However, their shallowness and/or stoniness, and implicit low water holding capacity, are serious limitations. The natural vegetation on Leptosols varies with the climate but is generally richer on calcareous Leptosols than on acid ones. Earthworms, enchytraeid worms and arthropods are the chief soil organisms. The soil fauna may be temporarily inactive in dry spells.

Management and use of Leptosols

Leptosols have a resource potential for wet-season grazing and as forest land. Areas with Rendzic Leptosols in southeast Asia are planted to teak and mahogany; Rendzic Leptosols in the temperate zone are under (mainly) deciduous mixed forest whereas acid Lithic, Umbric and Dystric Leptosols are commonly under pine forest.

Erosion is the greatest threat to Leptosol areas, particularly in mountain regions in the temperate zone where high population pressure (tourism), overexploitation and increasing environmental pollution lead to increasing deterioration of forests and threaten large areas of vulnerable Leptosols.

Leptosols on hill slopes are generally more fertile than their counterparts on more level land. One or a few 'good' crops could perhaps be grown on such slopes but at the price of severe erosion. Steep slopes with shallow and stony soils can be transformed into cultivable land through terracing, the removal of stones by hand and their use as terrace fronts. Agro-forestry (a combination of rotation of arable crops and forest under strict control) holds promise but is largely still in an experimental stage. The excessive internal drainage of many Leptosols can cause drought even in a humid environment.

REGOSOLS (RG)

The Reference Soil Group of the Regosols is a taxonomic rest group containing all soils that could not be accommodated in any of the other Reference Soil Groups. In practice, Regosols are very weakly developed mineral soils in unconsolidated materials that have only an ochric surface horizon and that are not very shallow (*Leptosols*), sandy (*Arenosols*) or with fluvic properties (*Fluvisols*). Regosols are extensive in eroding lands, in particular in arid and semi-arid areas and in mountain regions. Internationally, Regosols correlate with soil taxa that are marked by incipient soil formation such as 'Entisols' (USA), 'skeletal soils' (Australia), 'Rohböden' (Germany), and 'Sols peu évolués régosoliques d'érosion' or even 'Sols minéraux bruts d'apport éolien ou volcanique' (France).

Definition of Regosols#

Being a taxonomic rest group, Regosols are not defined in terms of their soil properties but are rather described in terms of properties that they do *not* have. For all practical purposes, Regosols are soils in unconsolidated mineral material of some depth, excluding coarse textured materials and materials with *fluvic properties,* and have no diagnostic horizons other than an *ochric horizon*.

Common soil units:
Gelic*, Leptic*, Hyposalic*, Gleyic*, Thaptovitric*, Thaptoandic*, Arenic*, Aric*, Garbic*, Reductic*, Spolic*, Urbic*, Tephric*, Gelistagnic*, Stagnic*, Humic*, Gypsiric*, Calcaric*, Takyric*, Yermic*, Aridic*, Hyperochric*, Anthropic*, Skeletic*, Hyposodic*, Vermic*, Dystric*, Eutric*, Haplic*.

See Annex 1 for key to all Reference Soil Groups
@ Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifiers for naming soil units; see Annex 3 for full definition.

Summary description of Regosols

Connotation: soils in the weathered shell of the earth; from Gr. *rhegos*, blanket.

Parent material: unconsolidated, finely grained weathering material.

Environment: all climate zones without permafrost and at all elevations. Regosols are particularly common in arid areas, in the dry tropics and in mountain regions.

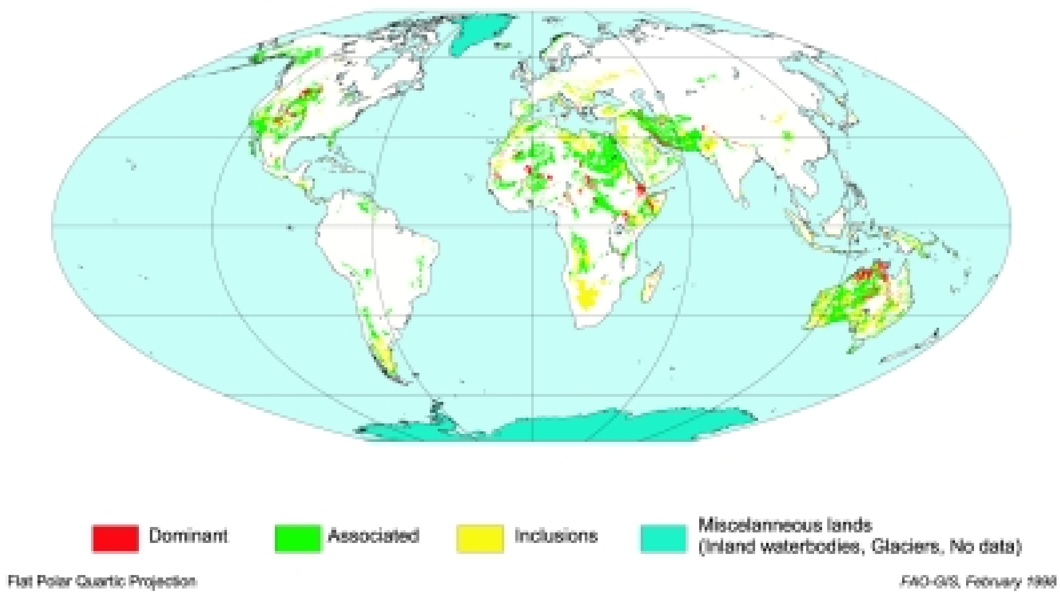
Profile development: AC-profiles with no other diagnostic horizon than an ochric surface horizon. Profile development is minimal as a consequence of young age and/or slow soil formation e.g. because of prolonged drought.

Use: land use and management vary widely. Some Regosols are used for capital-intensive irrigated farming but the most common land use is low volume grazing. Regosols in mountain areas are best left under forest.

Regional distribution of Regosols

Regosols cover an estimated 260 million hectares worldwide, mainly in arid areas in the mid-western USA, Northern Africa, the Near East and Australia. Some 50 million hectares of Regosols occur in the dry tropics and another 36 million hectares in mountain areas. The extent of most Regosol areas is only limited; consequently Regosols are common inclusions in other map units on small-scale maps. See Figure 1.

Figure 1
Regosols world-wide



Associations with other Reference Soil Groups

Being a taxonomic rest group, Regosols are found in association with a wide range of other Reference Soil Groups. However they are particularly common alongside other young or poorly developed soils in arid, degrading or eroding areas. As the listing of 'common soil units' (see above) suggests, many Regosols are intergrades, with properties tending towards those of *Cryosols* (cold regions), *Andosols, Leptosols* or *Umbrisols* (mountain regions), *Calcisols* or *Gypsisols* (arid regions), *Arenosols* and *Podzols* (sandy deposits) or *Cambisols*.

Genesis of Regosols

Soil forming processes have had a minimal effect on the properties of Regosols. This may have been caused by

1. conditions, which *retard soil formation* such as a dry and hot desert climate,
2. recent *truncation/exposure of the soil material*, or
3. steady *rejuvenation* of the soil material.

Profile development is limited to formation of a thin *ochric* surface horizon over (almost) unaltered parent material. The paucity of pedogenetic transformation products explains the low coherence of the matrix material and makes that soil colours are normally (still) determined by the composition of the mineral soil fraction. In regions with a considerable evaporation surplus over precipitation, some lime and/or gypsum may have accumulated at shallow depth in the profile but not to the extent that a calcic or gypsic horizon is present. Soils in recent deposits of mine waste, urban waste, landfills and dredgings that are (still) too young for soil formation to occur, are included in the Reference Soil Group of the Regosols.

Characteristics of Regosols

The great variation among Regosols (taxonomic rest group!) makes it virtually impossible to give a generalised account of Regosol characteristics.

The central concept of a Regosol is a deep, well-drained, medium-textured, non-differentiated mineral soil that has minimal expression of diagnostic horizons (other than an *ochric* surface horizon), properties or materials.

Some general observations:

- Parent material and climate dominate the morphology of Regosols. The content of weatherable minerals varies from low to extremely high (little transformation).
- In cool climates, the surface horizon contains poorly decomposed organic matter whereas (ochric) surface horizons tend to be thin, low in organic matter and generally weakly expressed in hot, dry climates.
- Regosols in dry regions have generally a higher base status than Regosols in more humid (mountain) regions.
- Low coherence of the matrix material makes most Regosols in sloping areas prone to erosion.
- Low water holding capacity and high permeability to water make most Regosols sensitive to drought.
- Many Regosols in colluvial material are prone to slaking in particular those in löss. This makes them sensitive to erosion in wet periods. Many Regosols form a hard surface crust early in the dry season; the crust hinders emergence of seedlings and infiltration of rain and irrigation water in the dry season.

Management and use of Regosols

Regosols in desert areas have minimal agricultural significance. Regosols in the steppe region with 500-1000 mm rainfall per annum need irrigation for crop production. The low moisture holding capacity of these soils calls for frequent applications of irrigation water; sprinkler or trickle irrigation solves the problem but is rarely economic. Where rainfall exceeds 750 mm per annum, the entire profile is raised to its (low) water holding capacity early in the wet season; improvement of dry farming practices may then be a better investment than installation of costly irrigation facilities.

Many Regosols are used for extensive grazing. Many Regosols on colluvial deposits in the loess belt of northern Europe and North America are cultivated; they are planted to small grains, sugar beet or fruit trees. Regosols in mountain regions are quite delicate and are best left under forest.

Set #5

MINERAL SOILS CONDITIONED BY LIMITED AGE

Cambisols

CAMBISOLS (CM)

The Reference Soil Group of the Cambisols holds soils with incipient soil formation. Beginning transformation of soil material is evident from weak, mostly brownish discolouration and/or structure formation below the surface horizon. Early soil classification systems referred to these 'brown soils' as 'Braunerde' (Germany), 'Sols bruns' (France), 'Brown soils'/'Brown Forest soils' (USA), or 'Brunizems' (Russia). FAO coined the name 'Cambisols'; USDA Soil Taxonomy classifies these soils as 'Inceptisols'.

Definition of Cambisols[#]

Soils having
- a *cambic*[@] horizon; or
- a *mollic*[@] horizon overlying subsoil with low base saturation within 100 cm depth; or one of the following:
- an *andic*[@], *vertic*[@] or *vitric*[@] horizon starting between 25 and 100 cm below the surface; or
- a *plinthic*[@], *petroplinthic*[@] or *salic*[@] or *sulfuric*[@] horizon starting between 50 and 100 cm below the soil surface, in the absence of loamy sand or coarser material above these horizons.

Common soil units:
Andic*, Aridic*, Calcaric*, Chromic*, Dystric*, Endosalic*, Eutric*, Ferralic*, Fluvic*, Gelic*, Gelistagnic*, Gleyic*, Gypsiric*, Haplic*, Hyperochric*, Leptic*, Mollic*, Plinthic*, Rhodic*, Skeletic*, Sodic*, Stagnic*, Takyric*, Vertic*, Vitric*, Yermic*.

[#] See Annex 1 for key to all Reference Soil Groups.
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifiers for naming soil units; see Annex 3 for full definition.

Summary description of Cambisols

Connotation: soils with beginning horizon differentiation evident from changes in colour, structure or carbonate content; from L. *cambiare*, to change.

Parent material: medium and fine-textured materials derived from a wide range of rocks, mostly in colluvial, alluvial or aeolian deposits.

Profile development: ABC profiles. Cambisols are characterized by slight or moderate weathering of parent material and by absence of appreciable quantities of illuviated clay, organic matter, aluminium and/or iron compounds.

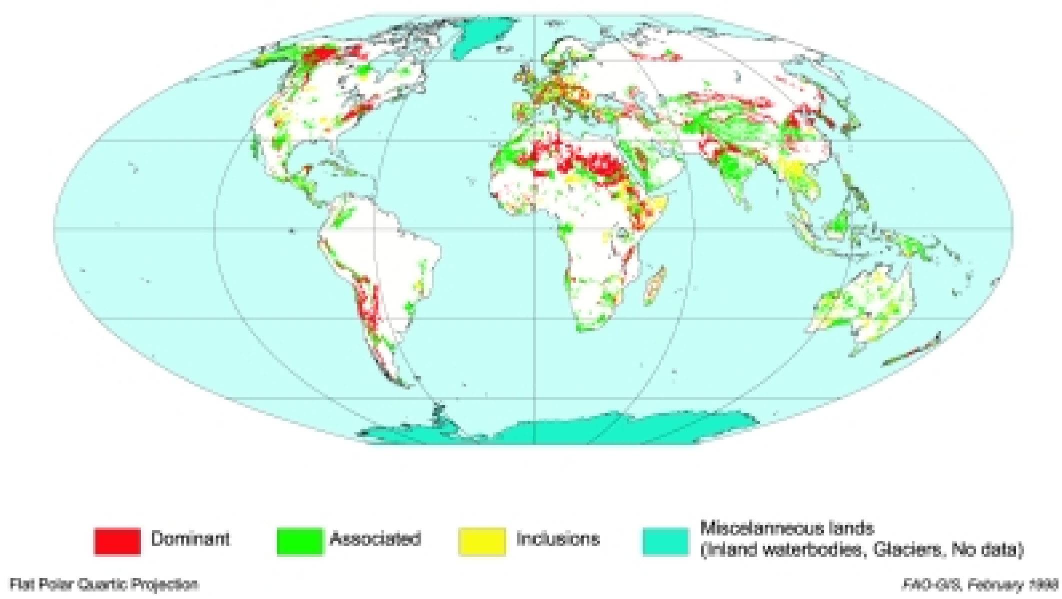
Environment: level to mountainous terrain in all climates and under a wide range of vegetation types.

Use: a wide variety of agricultural uses; climate, topography, shallowness, stoniness, or low base status may pose restrictions on land use. In steep lands mainly used for grazing and/or forestry.

Regional distribution of Cambisols

Cambisols cover an estimated 1.5 billion hectares worldwide. This Reference Soil Group is particularly well represented in temperate and boreal regions that were under the influence of glaciation during the Pleistocene, partly because the soil's parent material is still young but also because soil formation is comparatively slow in the cool, northern regions. Erosion and deposition cycles account for the widespread occurrence of Cambisols in mountain regions. Cambisols are less common in the tropics and subtropics The (young) alluvial plains and terraces of the Ganges-Brahmaputra system are probably the largest continuous surface of Cambisols in the tropics. Cambisols are also common in areas with active geologic erosion where they may occur in association with mature tropical soils. Figure 1 shows the word-wide occurrence of Cambisols.

Figure 1
Cambisols world-wide



Associations with other Reference Soil Groups

Cambisols in cool regions are particularly common in alluvial, colluvial and aeolian deposits. Cambisols in wetlands are associated with *Gleysols* and *Fluvisols*.

Cambisols in the arid (sub)tropics are found in young deposition areas but also in erosion areas where they form after genetically mature soils such as Luvisols have eroded away.

Cambisols in the humid tropics occur predominantly at medium altitudes in hilly and mountain regions but also in deposition areas and in eroding lands at lower altitude where they occur alongside genetically mature residual soils (e.g. *Acrisols* or *Ferralsols*).

Genesis of Cambisols

Most (not all) Cambisols are soils with beginning horizon differentiation; they are in a transitional stage of development, from a young soil to a mature soil with an argic, natric, spodic, or ferralic B-horizon. The first step in this development is the formation of a *cambic* subsurface horizon that is to be regarded as a 'minimum B-horizon'. Nonetheless, a cambic horizon can be quite stable, viz. where pedogenetic development is slow because of low temperatures, low precipitation, impeded drainage, highly calcareous or weathering-resistant parent materials, or where slow but continuous erosion is in equilibrium with weathering processes.

In practice, a cambic horizon is any section of a soil profile situated between an A-horizon and a relatively unaltered C-horizon, that has soil structure rather than rock structure and a colour that differs from that of the C-horizon.

Note that a cambic horizon can also occur in other Reference Soil Groups for which it is not a differentiating characteristic because other properties have higher priority. The fact that Cambisols key out late in the taxonomic hierarchy of Reference Soil Groups implies that this group includes many soils that just missed out on one or more requirements for other Reference Soil Groups.

Appreciable quantities of weatherable minerals and absence of any signs of *advanced* pedogenesis evidence the fact that Cambisols are in an early stage of soil formation. There are, however, signs of *incipient* weathering/transformation of primary minerals in a situation of free internal and external drainage. Hydrolysis of iron-containing minerals (biotite, olivine, pyroxenes, amphiboles, etc) in a weakly acid environment produces ferrous iron that is oxidized to ferric oxides and hydroxides (e.g. goethite, haematite). This *'free iron'* coats sand and silt particles, and cements clay, silt and sand to aggregates. The soil becomes structured and yellowish brown to reddish in colour. Aluminium oxides and hydroxides, and silicate clays are formed in addition to ferric oxides. There may be some leaching of bases but no clear migration of Fe, Al, organic matter or clay. This oxidative weathering process is not limited to the cambic horizon; it occurs just as well in the A-horizon and may even be stronger there, but the dark colour of accumulated soil organic matter obscures its signs.

The processes that lead to formation of a cambic subsurface horizon are fundamentally the same in all climate zones but the intensities of chemical and biological transformations are considerably greater in the (humid) tropics than elsewhere. Cambisols in the humid tropics can form in a few years time. Those in cool and/or dry regions require more time, *inter alia* because soil formation is halted for shorter or longer periods.

Characteristics of Cambisols

Morphological characteristics

The 'typical' Cambisol profile has an ABC horizon sequence with an ochric, mollic or umbric A-horizon over a cambic B-horizon that has normally a yellowish-brown colour but that may also be an intense red. Cambisols in poorly drained terrain positions may show *'redoximorphic'* features. The soil texture is loamy to clayey. Signs of beginning clay illuviation may be detectable in the cambic horizon but the clay content is normally (still) highest in the A-horizon.

Mineralogical, physical and chemical characteristics

It is not well possible to sum up all mineralogical, physical and chemical characteristics of Cambisols in one generalised account because Cambisols occur in such widely differing environments. However:

- most Cambisols *contain at least some weatherable minerals* in the silt and sand fractions.
- most Cambisols *occur in regions with a precipitation surplus* but in *terrain positions that permit surficial discharge of excess water*.
- most Cambisols *are medium-textured* and have a *good structural stability, a high porosity, a good water holding capacity and good internal drainage*.
- most Cambisols have a *neutral to weakly acid soil reaction*, a satisfactory chemical fertility and an active soil fauna.

Note that there are numerous exceptions to the above generalisations !

Management and use of Cambisols

By and large, Cambisols make good agricultural land and are intensively used. The Eutric Cambisols of the Temperate Zone are among the most productive soils on earth. The Dystric Cambisols, though less fertile, are used for (mixed) arable farming and as grazing land. Cambisols on steep slopes are best kept under forest; this is particularly true for Cambisols in highlands.

Vertic and Calcaric Cambisols in (irrigated) alluvial plains in the dry zone are intensively used for production of food and oil crops. Eutric, Calcaric and Chromic Cambisols in undulating or hilly (mainly colluvial) terrain are planted to a variety of annual and perennial crops or are used as grazing land.

Dystric and Ferralic Cambisols in the humid tropics are poor in nutrients but still richer than associated Acrisols or Ferralsols and they have a greater cation exchange capacity. Many Gleyic Cambisols in alluvial plains make productive ‘paddy soils’.

Set #6

Mineral Soils conditioned by a Wet (Sub)Tropical Climate

Major landforms in the (sub-)humid tropics

Large parts of the humid and sub-humid tropics belong to one of three morphostructural units:

1. *'Precambrian shields'* constitute major parts of eastern South America, equatorial Africa, and central and southern India;
2. *'Young alpine fold belts'* e.g. the equatorial Andes and Central America, and greater parts of Southeast Asia;
3. *'Tropical alluvial plains'* comprising *fluvial sedimentary basins* such as the Amazon basin, the Congo basin and the Indus-Ganges basin, and *coastal plains*, e.g. the coastal plains of the Guyana's, the Niger delta and the Mekong delta.

Landforms in *high* mountain areas were discussed in an earlier chapter as were the alluvial lowlands. The present chapter discusses common landforms on Precambrian shields and in the lower ranges of Alpine fold belts (below 3000 meters) in the humid and seasonally dry tropics.

Landforms on Precambrian shields

Precambrian shields, or '*cratons',* constitute the oldest cores of continents; they are remnants of mountains that formed more than 600 million years ago and that have since eroded to undulating plains that rise up to only a few hundred meters above the present sea level. The lithospheric plates on which the shields rest move over the Earth's surface at a rate of several centimetres per year. In places, this movement produces weak stretches that become subject to rifting and subsidence. Such locations are preferential sites for formation of sedimentary river basins (e.g. the Amazon basin) or for deposition of rocks (e.g. during the Mesozoic in South Sweden).

The Precambrian era spans 80 percent of the geological history of the Earth and includes many periods of mountain building, erosion and sedimentation. Igneous, sedimentary and metamorphic rocks of Precambrian age exist in great variety but crystalline (plutonic and metamorphic) rocks predominate.

By and large, Precambrian formations belong to one or more the following:

1. *'High-grade metamorphic belts'*. These are normally narrow belts (only tens of kilometres across) that consist for the greater part of strongly metamorphosed rocks, which originate from sedimentary rocks. The lithology of these belts is diverse with metamorphosed limestone (marbles) and/or metamorphosed sandstone (quartzites) alongside rocks that are not of sedimentary origin such as metamorphosed basalt flows or dykes (amphibolites) and strongly metamorphosed rocks, e.g. gneiss, granulites and granitoid gneiss. The considerable variation in mineralogical and chemical/physical properties of these rocks explains the wide variety of landforms and soils.

2. *'Greenstone belts'.* These are narrow belts (a few tens or hundreds of kilometres across) that can stretch over thousands of kilometres. Greenstone belts consist mainly of metamorphosed volcanic rocks, notably basalt and andesite, with varying proportions of intercalated sedimentary rocks that have normally been converted to schist and phyllites by low-grade metamorphism. A characteristic feature of greenstone belts is the occurrence of *tonalite* intrusions, normally with oval outlines on the geological map. (Tonalite is a granite-like rock of plutonic origin and usually has plagioclase as the sole feldspar. As plagioclase weathers easily, tonalite areas are more deeply weathered than nearby granite areas). Examples are the Koidu Basin in Sierra Leone and the Brokopondo lake area in Surinam.
3. *'Granite areas',* often associated with either *migmatites* (i.e. banded rocks formed through partial melting of sediments deep in the crust), or granitoid gneiss.
4. *'Platform areas'* with horizontal sedimentary rocks, commonly sandstones, on top of the Precambrian shield; adjacent uncovered shield areas are referred to as *'basement areas*'.

Tropical shield areas were mainly modified by chemical weathering and by fluvial and marine processes (glacial, periglacial and aeolian processes were insignificant in the recent past). How water could shape the surface in tropical shield areas is largely explained by

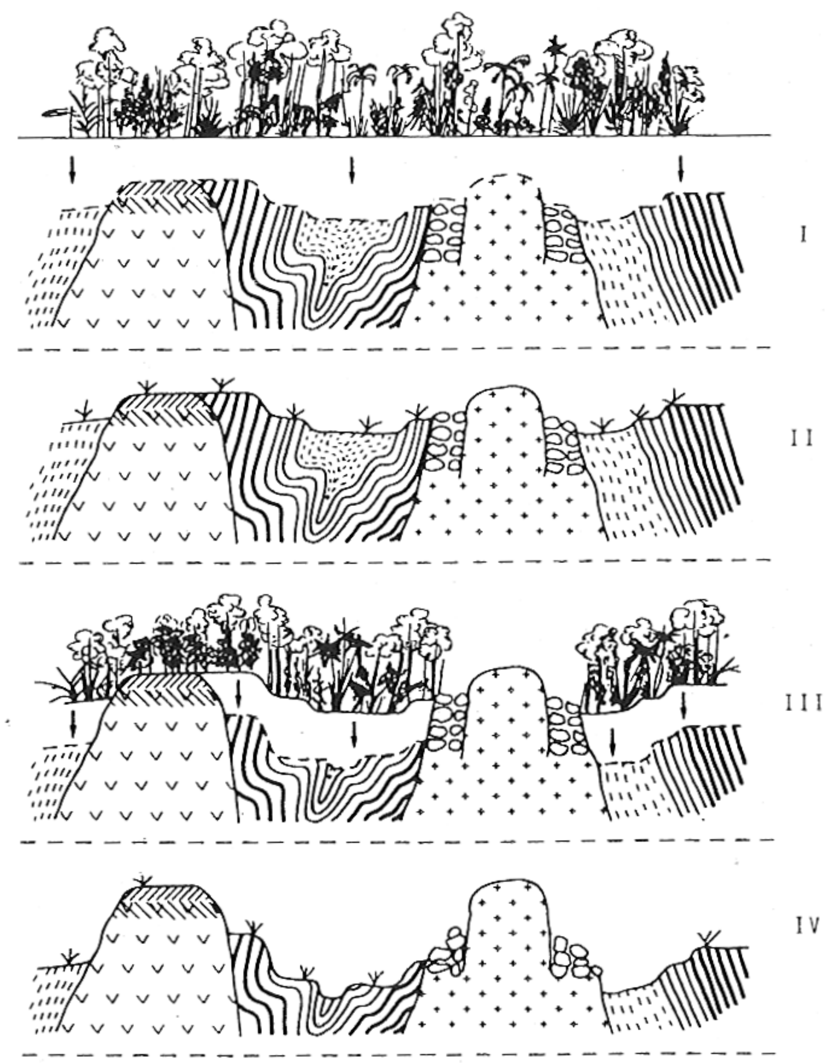
- the *amount and intensity of precipitation*, and
- the *presence or absence of a protective vegetation cover*.

In areas under rain forest, most precipitation is intercepted by the canopy from where it trickles down to the forest floor and infiltrates into the soil. There, it promotes rapid chemical weathering of rocks because its low ionic strength and comparatively high temperature promote hydrolysation processes. The *'saprolite'* (i.e. 'rotten rock') under a rain forest may extend down to a depth of tens or even hundreds of metres. The saprolite is usually less thick on granite (say, 10-20 metres) than on metamorphic rock (40-70 metres; data from Surinam). Long periods of strong chemical weathering and little, if any, surface runoff have gradually deepened the weathering front, a process known as *'etching'*. The saprolite is normally clayey because feldspars and ferromagnesian minerals have weathered to clay minerals and (sesqui-)oxides. The sand content of the saprolite reflects the content of coarse quartz in the original parent rock. Thoroughly weathered saprolites are chemically very poor, despite their lush (rain forest) vegetation cover.

Note that the vegetation is less densely spaced *in arid areas* because each individual plant needs a larger volume of soil for its water supply. A single downpour on such open land can cause torrential *'sheet floods'*. In the intermediate situation, i.e. in *semi-arid savannah and prairie areas*, surface runoff and denudation are particularly severe. On sites with sparse vegetation and distinct surface relief, the rate of topsoil erosion may well exceed the rate of weathering. This results in *'stripping'* of the land; etching is more common under protective vegetation types, e.g. under rain forest.

Figure 1 explains how summit levels were formed after prolonged, differential etching and stripping. *Note that* the balance between etching and stripping was almost certainly different from the present situation during long periods in the past.

Figure 1
Development of summit levels by differential etching and stripping.
(Kroonenberg and Melitz, 1983)



Many shield areas in tropical regions include vast, dissected etch-plains with solitary elevated remnants that are either bare, dome-shaped granite hills (*'inselbergs'*) such as the 'sugar loaf' of Rio de Janeiro, or heaps of huge granite boulders known as *'tors'*. The etch-plains consist of deep, flat or undulating, residual weathering crust dissected by a network of V-shaped valleys that are only a few metres deep. Where the natural drainage pattern is widely spaced, remnants of the original flat surface may still be in place but only rounded, convex hills remain in areas with more densely spaced gullies. *Note that* natural drainage patterns are normally conditioned by underlying bedrock: low ridges and depressions form upon differential etching and stripping of weathering-resistant rocks.

The occurrence of isolated inselbergs and tors amidst vast expanses of undulating lowland is more common in savannah regions than in areas with rain forest. Valleys in savannah regions (called *'dambos'* or *'vleis'* in large parts of Africa) tend to be broad and shallow as a result of colluviation and slope wash. The widespread occurrence of *'laterite plateaus'* is an indication of climate fluctuations in the past. Strongly weathered saprolite with quartz-rich clays (*'plinthite'*) formed during humid eras. In the (now) semi-arid tropics, much plinthite has subsequently hardened to *'ironstone'*. Many plateaux are weathering residues protected by an ironstone cap. In places they formed through relief inversion of iron-cemented valley fills.

Landforms in alpine fold belts (lower than 3000 metres)

High mountain areas in tropical regions became glaciated in the Pleistocene but tracts lower than 3,000 meters above the present mean sea level were never reached by descending valley glaciers. In lower mountain areas, the relation between rainfall and land surface transformation is similar to that in shield areas. Rain forest is the preponderant vegetation type and infiltration water reaches great depths. Weathering is rapid and fresh rock is difficult to find, even in deeply dissected terrain. The lower foot slopes of the Andes and Himalayas and uplands in Africa present numerous examples. The dominant geomorphic controls in humid tropical mountain areas are:

1. strong *tectonic uplift*;
2. rapid *incision of rivers*, and
3. *undercutting of slopes* and subsequent *mass movement*.

Landslides and mudflows have shaped many slope sites in the humid and seasonally dry tropics. These phenomena were triggered by torrential rainfall that saturated the weathering crust with water. Often, seismic events such as earthquakes gave the final stimulus for sliding. Shallow landslides are common in forested mountain areas, e.g. in New Guinea, Sulawesi, Hawaii or the Andes; a provisional chronology can often be established by simply considering degrees of forest regeneration. *Note that*, contrary to common belief, forest vegetation cannot prevent landslides from happening because the sliding landmass detaches itself at the *'weathering front'*, i.e. the contact plane between saprolite and fresh rock that is beyond the reach of tree roots.

It is generally true that regions with crystalline rocks have symmetrical hills with sharp crests and rectilinear slopes, separated by steep V-shaped valleys. Joints and faults in the underlying rocks determine the drainage pattern.

Weathering mantles tend to be less deep over siliceous sedimentary rocks than over crystalline rocks. The alternation of resistant and less resistant strata is the main controlling factor in folded sedimentary rocks. Nice examples can be seen in areas with alternating limestone and sandstone ridges as extend from India through Burma, Thailand and Laos all the way to Vietnam. Humid tropical areas with calcareous rocks may show abundant *'karst'* phenomena such as sink holes and caves formed upon dissolution of limestone. *'Tower karst'* with residual limestone rocks standing in the landscape as towers (e.g. in Guilin, China) formed upon advanced dissolution of limestone. Similarly convincing are the 'cockpit' or 'mogote' hills at Bohol (Philippines) and the razor-sharp limestone ridges of the 'broken-bottle country' of New Guinea. *Note that* such extreme karstic landscapes can only develop in uplifting areas.

The advanced weathering of rocks in the (sub-)humid tropics produced ‘typical’ tropical soils: red or yellow in colour and strongly leached. Additional features: they are deep, finely textured, contain no more than traces of weatherable minerals, have low-activity clays, less than 5 percent recognisable rock structure and gradual soil boundaries. Differences between soils in the (sub-)humid tropics can often be attributed to differences in lithology and/or (past) moisture regime.

PLINTHOSOLS (PT)

The Reference Soil Group of the Plinthosols holds soils that contain *'plinthite'*, i.e. an iron-rich, humus-poor mixture of kaolinitic clay with quartz and other constituents that changes irreversibly to a hardpan or to irregular aggregates on exposure to repeated wetting and drying. Internationally, these soils are known as 'Groundwater Laterite Soils', 'Lateritas Hydromorficas' (Brazil), 'Sols gris latéritiques' (France), 'Plinthaquox' (USA, Soil Taxonomy) or as Plinthosols (FAO).

Definition of Plinthosols[#]

Soils having
a *petroplinthic*[@] horizon starting within 50 cm from the soil surface, or
a *plinthic*[@] horizon starting within 50 cm from the soil surface, or
a *plinthic*[@] horizon starting within 100 cm from the soil surface underlying either an *albic*[@] horizon or a horizon with *stagnic*[@] properties.

Common soil units:
Petric*, Endoduric*, Alic*, Acric*, Umbric*, Geric*, Stagnic*, Abruptic*, Pachic*, Glossic*, Humic*, Albic*, Ferric*, Skeletic*, Vetic*, Alumic*, Endoeutric*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups.
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Plinthosols

Connotation: soils with *'plinthite'*; from Gr, *plinthos*, brick.

Parent material: plinthite is more common in weathering material from basic rocks than from acidic rocks. In any case it is crucial that sufficient iron is present, originating either from the parent material itself or brought in by seepage water from elsewhere.

Environment: formation of plinthite is associated with level to gently sloping areas with fluctuating groundwater. *'Petroplinthic'* soils with continuous, hard *'ironstone'* form where plinthite becomes exposed to the surface, e.g. on erosion surfaces that are above the present drainage base. *'Skeletic'* soil units having a layer of hardened plinthite concretions occur mostly in colluvial or alluvial deposits. Soft plinthite is associated with rain forest areas; petroplinthic and skeletic soils are more common in the savannah zone.

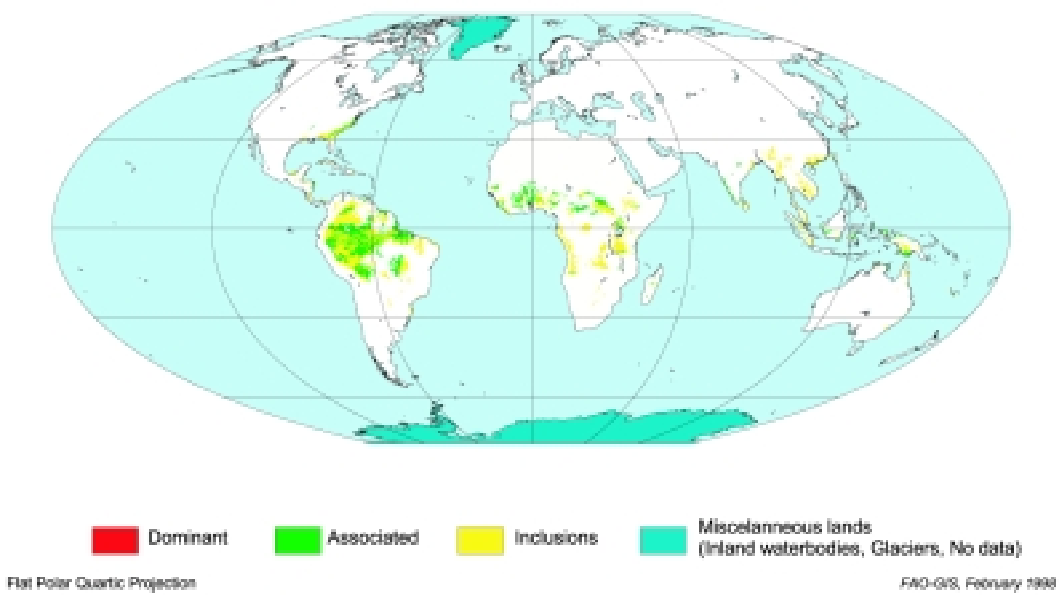
Profile development: mostly A(E)BC-profiles with segregation of plinthite at the depth of groundwater fluctuation. Hardening of plinthite to *petroplinthite* takes place upon repeated drying and wetting, commonly after geological uplift of the terrain and/or climate change towards drier conditions.

Use: mostly low volume grazing. Arable cropping is hindered by poor rooting conditions associated with frequent water logging and/or excessive stoniness and low chemical soil fertility.

Regional distribution of Plinthosols

The global extent of soils with plinthite is estimated at some 60 million hectares. Soft plinthite is most common in the wet tropics, notably in the eastern Amazon basin, the central Congo basin and parts of Southeast Asia. Extensive areas of hardened plinthite occur in the Sudano-Sahelian zone where petroplinthite forms hard caps on top of uplifted/exposed landscape elements. Similar soils occur on the Indian subcontinent, and in drier parts of Southeast Asia and northern Australia. See Figure 1.

Figure 1
Plinthosols world-wide



Associations with other Reference Soil Groups

Plinthosols occur in tropical regions with 'red tropical soils' such as Ferralsols, Alisols, Acrisols and Lixisols. Soils with residual 'soft' plinthite occur in less well-drained positions in the landscape; they have *gleyic* or *stagnic* properties and many of these are linked to Gleysols. Well-drained soils with abundant *loose* iron concretions (*'pisolithes'* or *'pea iron'*) in tropical and subtropical regions are commonly formed in plinthitic material that was dislocated, hardened, transported and finally deposited as alluvial or (more commonly) colluvial soil parent material. Such soils are related to Plinthosols but may have to be classified as Plinthic soil units of other Reference Soil Groups. Petric Plinthosols in eroding areas occur together with Leptosols and/or leptic units of other soils.

GENESIS OF PLINTHOSOLS

Areas where the formation of plinthite is still active have a hot and humid climate with a high annual rainfall sum and a short dry season. Buchanan (1807) coined the term *'laterite'* for an iron-rich, humus-poor mixture of kaolinitic clay and quartz that was used as a building material in western India (Lat. *'later'* means 'brick'). The term 'plinthite' was introduced much later to evade confusion created by different interpretations of the term 'laterite' and its many derivatives.

Formation of plinthite

Plinthite forms in perennially moist (sub)soil layers. Formation of plinthite involves the following processes:

1. *accumulation of sesquioxides* through
   - *removal of silica and bases* through advanced hydrolysis and discharge of dissolved weathering products. This results in *relative accumulation* of weathering resistant sesquioxides, quartz and kaolinite, or
   - *absolute accumulation* of sesquioxides through enrichment from outside, and
2. *segregation of iron* (mottles) by alternating reduction and oxidation. Under conditions of water saturation, much of the iron is in the ferrous form and 'mobile'. This iron precipitates as ferric oxide when/where conditions become drier and will not or only partially re-dissolve when conditions become wetter again. This explains why plinthite shows a typical redistribution pattern with red mottles in a platy, polygonal or reticulate configuration.

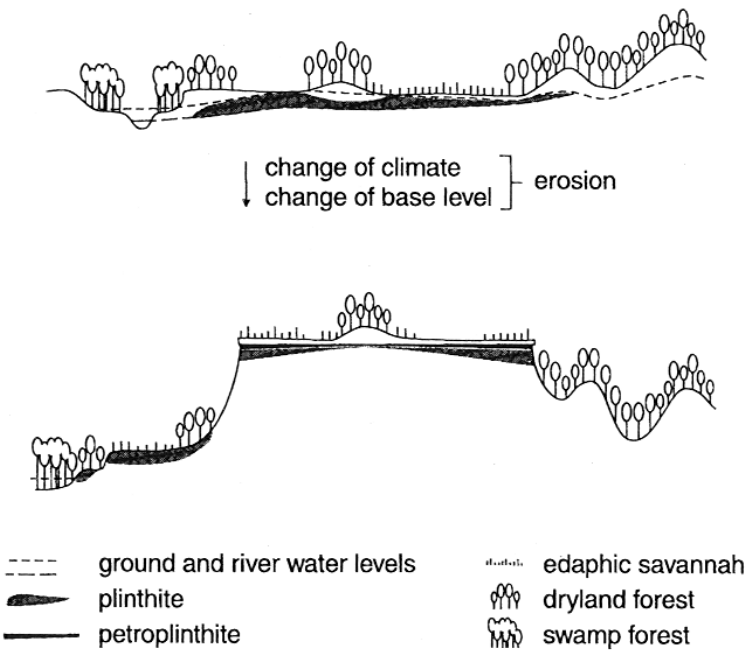
Hardening of plinthite to petroplinthite

In its unaltered form, plinthite is firm but can be cut with a spade. If the land becomes drier, e.g. because of a change in base level and/or a change in climate, plinthite hardens irreversibly to petroplinthite. Hardening of plinthite involves the following processes:

1. *crystallization of amorphous iron compounds* to continuous aggregates of iron oxide minerals, especially *goethite*, and
2. *dehydration of goethite (FeOOH) to hematite (Fe_2O_3)* and, if present, of gibbsite ($Al_2O_3.3H_2O$) to boemite ($Al_2O_3.H_2O$).

Hardening of plinthite is often initiated by removal of the vegetation, especially forest, as this triggers erosion of the surface soil and exposure of plinthite to the open air. Hardened plinthite occurs in many tropical soils, either in a 'skeletic' (concretionary) form or as continuous petroplinthite. Plinthosols with soft plinthite are indigenous to the rain forest zone. Soils with petroplinthite are especially abundant in the transition zone from rain forest to savannah, notably in dry areas that were once much wetter, e.g. in sub-Sahelian Africa; plinthite that was once at some depth hardened and became exposed as a thick ironstone cap that resists (further) erosion. This may ultimately lead to inversion of the original relief: depression areas where plinthite formed are shielded against erosion by their ironstone caps and become the highest parts of the landscape. See Figure 2.

Figure 2
Inversion of relief in an eroding landscape: hardening of exposed plinthite produces a protective shield against further erosion



CHARACTERISTICS OF PLINTHOSOLS

Morphological characteristics

Plinthite is red mottled clay but not all red mottled clay is plinthite. It is not always easy to distinguish between 'normal' mottled clay, plinthite and ironstone gravel because they grade into each other. Field criteria for identification of plinthite are:

- red mottles are firm or very firm when moist and hard or very hard when dry
- they *can be cut with a knife* but only with difficulty
- they *have sharp boundaries*
- they *hardly stain the fingers* when rubbed, and
- they *do not slake in water*.

The most obvious distinguishing feature of plinthite is of course, that it hardens irreversibly to petroplinthite upon repeated wetting and drying but this cannot always be ascertained in the field.

Petroplinthite (also referred to as 'ironstone', 'laterite', 'murram' or 'ferricrete') can be divided on basis of its morphology into

1. '*hyperplinthic' massive iron pans* that are either
   - *residual*: a continuous layer of indurated plinthite. Iron oxides are the main cementing agent; organic matter is absent or present only in traces. The layer may be massive or

show a reticulate or interconnected platy or columnar pattern that encloses lighter coloured, non-indurated material, or
   - *secondary*: (mostly) colluvial ironstone gravel, stones and boulders formed by disintegration of a massive iron pan, that are re-cemented together.
2. *'orthiplinthic' discontinuous petroplinthite* either
   - *residual:* gravel formed by in situ hardening of plinthite. Red mottles constitute a considerable part of the soil volume and are not interconnected. The gravels are rounded (*'pisolithes'* or *'pea iron'*) or irregular nodules, or
   - *secondary:* (mostly) colluvial ironstone gravel, stones and boulders that are not cemented together.

Mineralogical characteristics

Plinthite and petroplinthite have high contents of hydrated Fe- and Al-oxides (*'sesquioxides'*). Free iron is present as oxide minerals, notably *lepidocrocite* (FeOOH), *goethite* (FeOOH) and *hematite* (Fe_2O_3); free aluminium occurs in *gibbsite* ($Al_2O_3.3H_2O$) and/or *boehmite* ($Al_2O_3.H_2O$). Old ironstone crusts contain more hematite and boehmite and less sesquioxides than plinthite. Free silica is present as quartz inherited from the parent material. Easily weatherable primary minerals have disappeared; the dominant clay mineral is well-crystallized kaolinite.

Hydrological characteristics

Plinthosols with 'soft' plinthite occur in bottomlands, in regions with a distinct annual precipitation surplus over evaporation. Percolating rainwater may cause eluviation symptoms such as an *albic* subsurface horizon, often under an *umbric* surface horizon. Plinthosols in bottomlands tend to develop *gleyic* or *stagnic* properties.

Physical characteristics

Soft plinthite is dense and obstructs deep percolation of water and penetration of plant roots. The specific density of petroplinthite ranges from 2.5 to 3.6 Mg m^{-3} and increases with increasing iron content. Plinthosols with continuous ironstone at shallow depth are generally unsuitable for arable uses on account of their low water storage capacity.

Chemical characteristics

All Plinthosols have high contents of iron and/or aluminium, with proportions varying from more than 80 percent iron oxides with little aluminium to about 40 percent of each. Most Plinthosols have poor cation exchange properties and low base saturation but there are exceptions, e.g. Endoeutric soil units.

Management and use of Plinthosols

Plinthosols come with considerable management problems. Poor natural soil fertility, water logging in bottomlands and drought on shallow and/or skeletal Plinthosols are serious limitations. Many Plinthosols outside the wet tropics have shallow, continuous petroplinthite, which limits their rootable soil volume to the extent that arable farming is no longer possible; such land can at best be used for low volume grazing. The stoniness of many Plinthosols is an added complication. Skeletic soils, many with high contents of pisolithes (up to 80 percent) are still planted to food crops and tree crops (e.g. cocoa in West Africa, cashew in India) but the crops suffer from drought in the dry season.

Civil engineers have a different appreciation of petroplinthite and plinthite than agronomists. To them, plinthite is a valuable material for making bricks (massive petroplinthite can also be cut to building blocks); ironstone gravel can be used in foundations and as surfacing material on roads and airfields. In some instances plinthite is a valuable ore of iron, aluminium, manganese and/or titanium.

FERRALSOLS (FR)

The Reference Soil Group of the Ferralsols holds the 'classical', deeply weathered, red or yellow soils of the humid tropics. These soils have diffuse horizon boundaries, a clay assemblage dominated by low activity clays (mainly kaolinite) and a high content of sesquioxides. Local names usually refer to the colour of the soil. Internationally, Ferralsols are known as Oxisols (Soil Taxonomy, USA), Latosols (Brazil), Sols ferralitiques (France), Lateritic soils, Ferralitic soils (Russia) and Ferralsols (FAO).

Definition of Ferralsols#

Soils
1. having a *ferralic*@ horizon at some depth between 25 and 200 cm from the soil surface, and
2. lacking a *nitic*@ horizon within 100 cm from the soil surface, and
3. lacking an *argic*@ horizon that has 10 percent or more water-dispersible clay within 30 cm from its upper boundary unless the soil material has *geric*@ properties or contains more than 1.4 percent organic carbon.

Common soil units:
Gibbsic*, Geric*, Posic*, Histic*, Gleyic*, Andic*, Plinthic*, Mollic*, Acric*, Lixic*, Umbric*, Arenic*, Endostagnic*, Humic*, Ferric*, Vetic*, Alumic*, Hyperdystric*, Hypereutric*, Rhodic*, Xanthic*, Haplic*.

See Annex 1 for key to all Reference Soil Groups
@ Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Ferralsols

Connotation: red and yellow tropical soils with a high content of sesquioxides; from L. *ferrum*, iron and *aluminium*, alum.

Parent material: strongly weathered material on old, stable geomorphic surfaces; more in weathering material from basic rock than in siliceous material.

Environment: typically in level to undulating land of Pleistocene age or older; less common on younger, easily weathering rocks. Perhumid or humid tropics; minor occurrences elsewhere are considered to be relics from past eras with a wetter climate than today.

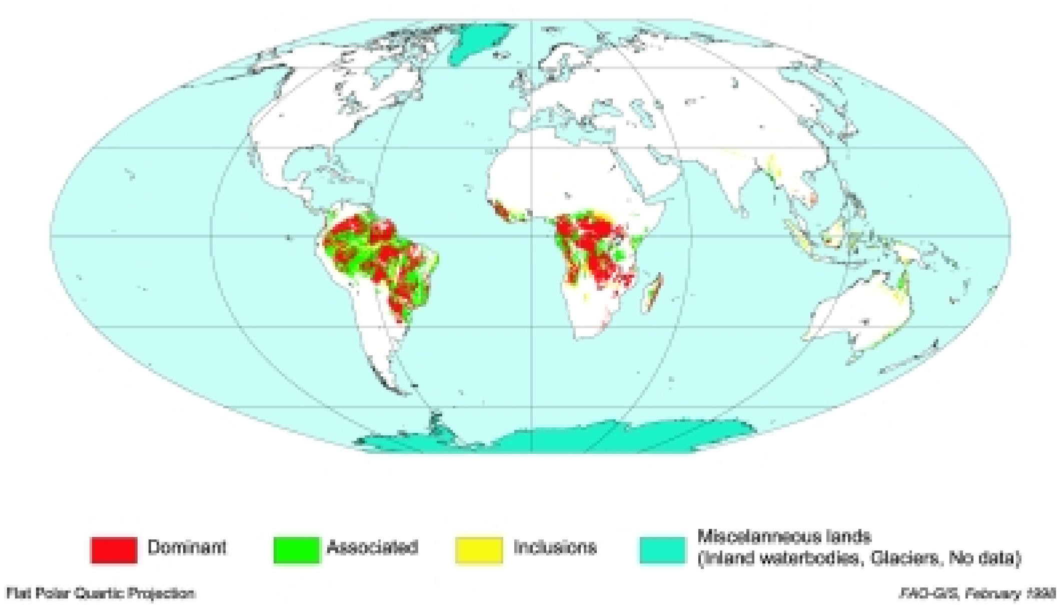
Profile development: ABC profiles. Deep and intensive weathering has resulted in a high concentration of residual, resistant primary minerals alongside sesquioxides and well-crystallized kaolinite. This mineralogy and the low pH explain the stable microstructure (pseudo-sand) and yellowish (goethite) or reddish (hematite) soil colours.

Use: Ferralsols have good physical properties but are chemically poor. Their low natural fertility and tendency to ‘fix’ phosphates are serious limitations. In natural systems, the limited stock of plant nutrients is in a constant process of ‘cycling’ with most nutrients contained in the biomass. Many Ferralsols are (still) used for shifting cultivation. Liming and full fertilisation are required for sustainable sedentary agriculture.

Regional distribution of Ferralsols

The worldwide extent of Ferralsols is estimated at some 750 million hectares, almost exclusively in the humid tropics on the continental shields of South America (Brazil) and Africa (Zaire, southern Central African Republic, Angola, Guinea and eastern Madagascar). Outside the continental shields, Ferralsols are restricted to regions with easily weathering basic rock and a hot and humid climate, e.g. in southeast Asia. See Figure 1.

Figure 1
Ferralsols world-wide



Associations with other Reference Soil Groups

Ferralsols tend to occupy the upper portions of stable land surfaces in the humid tropics where they occur alongside Acrisols (in lower positions or on more acidic parent rock such as gneiss) or Nitisols that evolved on top of more basic rock, e.g. dolerite. Clear zonality of Ferralsols and Acrisols exists on a continental scale. Ferralsols are dominant in (humid) Central Africa with Acrisols occurring in the sub-humid periphery of the Ferralsol area, extending into West and East Africa. In South America, Ferralsols are prevalent in the more humid eastern Amazon Basin and Acrisols in the western Amazon.

Genesis of Ferralsols

Water affects primary minerals through the processes of *'hydration'* and *'hydrolysis'*.

- *hydration* is water absorption by solid particles.
- *hydrolysis* is the process of H^+-ions penetrating minerals such as feldspars, which then release bases (K, Na, Ca, Mg). Hydrolysis weakens the structure of the minerals because the hydrogen ion is much smaller than the cations it replaces. Dissolution of Si and Al are accelerated in the process.

'Ferralitization' is hydrolysis in an advanced stage. If the soil temperature is high and percolation intense (humid climate!), all weatherable primary minerals will ultimately dissolve and be removed from the soil mass. Less soluble compounds such as iron and aluminium oxides and hydroxides and coarse quartz grains remain behind. Ferralitization (or *'desilication'* as it is also called) is furthered by the following conditions:

1. *Low soil-pH and low concentrations of dissolved weathering products* in the soil solution promote desilication and build-up of high levels of (residual) Fe and Al. CO_2 in the soil (from respiration by roots and soil organisms feeding on organic matter) and percolating rainwater depress the pH of the soil and lower the concentrations of weathering products.
2. *Geomorphic stability* over prolonged periods of time is essential. Ferralitization is a very slow process, even in the tropics where high temperatures increase reaction rates and solubility limits. *Note that* old erosion surfaces are more common in the tropics than in temperate regions where recent glacial processes re-shaped the landscape.
3. *Basic parent material* contains relatively much iron and aluminium in easily weatherable minerals, and little silica. Ferralitization proceeds much slower in acidic material that contains more quartz. Even though most silica is leached from the soil (hence 'desilication'), the silica content of the soil solution remains higher than in soils in basic material. This silica combines with aluminium to the 1:1 clay mineral kaolinite (*'kaolinitization'*), in particular where internal drainage is impeded and dissolved silica is less quickly removed (see Table 1).

TABLE 1
Schematic occurrence of gibbsite ($Al(OH)_3$) and kaolinite in strongly weathered soils with various drainage conditions

Parent material	Internal drainage			
	very good	good	moderate	poor
Mafic ('basic') rock	Gibbsite	gibbsite	kaolinite	2:1 clays
Felsic ('acidic') rock	gibbsite	kaolinite	kaolinite	kaolinite

Ferrihydrite ($Fe(OH)_3$; see also the chapter on Andosols) is a common weathering product of iron-rich parent material. Hematite (Fe_2O_3, the mineral that gives many tropical soils their bright red colour) forms out of ferrihydrite if:

1. the *iron concentration is high*, and
2. the *organic matter content is low* (Fe-humus complexes inactivate Fe !), and
3. the *temperature is high* (accelerates dehydration of ferrihydrite and decomposition of organic matter), and
4. the *soil-pH is above 4.0* (else $Fe(OH)_2^+$-monomers are formed).

Goethite (FeOOH, more orange in colour than bright red hematite) is formed when one or more of the above conditions are not (fully) met.

Characteristics of Ferralsols

Morphological characteristics

Ferralsols are deep, intensely weathered soils. By and large, Ferralsols have the following characteristic features:

1. a *deep solum* (usually several meters thick) with *diffuse or gradual* horizon boundaries.
2. a *'ferralic' subsurface horizon*, reddish (hematite) or yellowish (goethite) in colour, with weak macro-structure and strong microstructure ('pseudo-silt' and 'pseudo-sand') and friable consistence. Soils with 60 percent or more clay 'feel loamy' and have similar pore volume and mechanical properties as medium or even light-textured soils.
3. *deep internal drainage* and absence of conspicuous mottles.

Mineralogical characteristics

Ferralsols are characterized by relative accumulation of stable primary and secondary minerals; easily weathering primary minerals such as glasses and ferro-magnesian minerals and even the more resistant feldspars and micas have disappeared completely. Quartz is the main primary mineral (if originally present in the parent rock). The clay assemblage is dominated by kaolinite, goethite, hematite and gibbsite in varying amounts, in line with the kind of parent rock and the drainage conditions (see also Table 1).

Hydrological characteristics

Most Ferralsols are clayey (a consequence of advanced weathering) and have strong water retention at permanent wilting point while the presence of micro-aggregates reduces moisture storage at field capacity. This explains their rather limited capacity to hold 'available' water (i.e. available to most crops); some 10 mm of 'available' water per 10 cm soil depth is 'typical'. Ferralsols are poorly equipped to supply crops with moisture during periods of drought, particularly those in elevated positions.

Physical characteristics

Stable micro-aggregates explain the excellent porosity, good permeability and favourable infiltration rates measured on Ferralsols. Soils with high contents of (positively charged) iron oxides and (negatively charged) kaolinite have stable soil structure due to bonding of opposite elements. Ferralsols with low contents of iron and/or organic matter as occur in Surinam and Brazil (Xanthic Ferralsols) have less stable structure elements, especially the sandy ones. Surface sealing and compaction become serious limitations if such soils are taken into cultivation.

The strong cohesion of (micro-)aggregates and rapid (re)flocculation of suspended particles complicate measurements of the particle size distribution of Ferralsol material. The clay content found after the removal of iron and addition of a dispersing chemical is known as the *'total clay'* content. The clay content found after shaking an aliquot of soil with distilled water (without removal of iron or addition of dispersion agents) is the *'natural clay'* content. The high degree of aggregation in ferralic subsurface horizons explains the low contents of natural clay (< 10 percent).

Chemical characteristics:

Ferralsols are chemically poor soils. The types and quantities of clay minerals, oxides and organic matter condition the exchange properties of soils. The total exchange capacity is composed of a *permanent* and a *variable* component:

- The *'permanent charge'* component is the result of isomorphic substitution, e.g. of Si^{4+} by Al^{3+} or Al^{3+} by Mg^{2+}, in the crystal lattices of clay minerals. The *negative* permanent charge is independent of soil-pH or ion concentrations of the soil solution. Kaolinite, the main clay mineral in Ferralsols, has only a very small permanent charge.

- The *'variable charge'* component is caused by:

1. *'dissociation of H^+-ions'* from molecules at the perifery of the exchange complex. Dissociation of H^+-ions creates negative exchange sites and is strongest at high concentrations of OH^- in the soil solution. It accounts for the *'pH-dependent'* component of the overall Cation Exchange Capacity (CEC).
2. *'protonation',* i.e. release of protons (H^+) by acid groups at the edges of clay particles, or by carboxylic or phenolic groups in organic matter, or by aluminium and iron hydroxides. Protonation contributes to the positive charge component.

The CEC-clay of a ferralic horizon may, by definition, not exceed 16 cmol(+)/kg clay. *Note that* CEC is determined in a 1M NH_4OAc solution buffered to pH 7; the field-pH of Ferralsols is normally much less than 7.

The net negative charge of the exchange complex is neutralized by exchangeable bases (Na^+, K^+, Ca^{2+}, Mg^{2+}) **plus** *'exchangeable acidity'* (Al^{3+} + H^+). The *'Effective CEC'* (ECEC), i.e. the sum of bases and exchangeable acidity, is thought to represent the soil's cation exchange capacity at field conditions.

Note that the ECEC of Ferralsols is much less than the CEC; actual cation adsorption is often a mere 3 or 4 cmol(+) per kg soil.

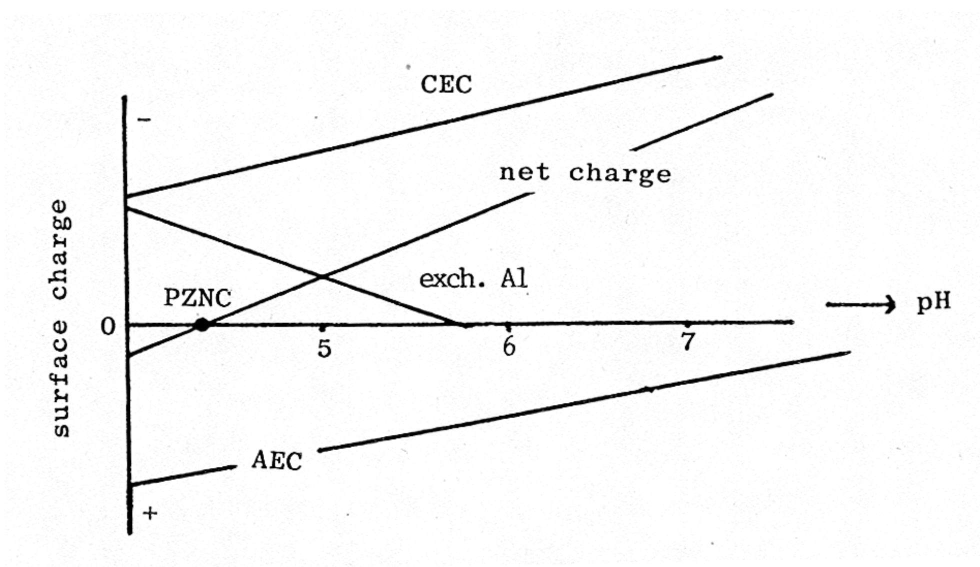
Protonation of hydroxylic groups at low pH-values may boost the soil's *'Anion Exchange Capacity'* (AEC) to the extent that the AEC equals or exceeds the CEC. This can be detected by comparing pH-values of two samples of the same soil, one in suspension in H_2O and the other in 1M KCl. $pH_{(KCl)}$ is less than $pH_{(H2O)}$ in soils with net negative charge (the 'normal' situation); the reverse is true in soils with net positive charge.

The following terminology is used in publications on the exchange properties of strongly weathered tropical soils:

- The pH value at which AEC fully compensates CEC (permanent plus variable charges) is called the *'point of zero net charge'* (PZNC).
- The difference between $pH_{(KCl)}$ and $pH_{(H2O)}$ is known as *'delta pH'*.

Figure 2 presents a schematic outline of the exchange characteristics of strongly weathered tropical soils in relation to soil-pH.

Figure 2
Schematic relation between exchangeable aluminium level, AEC, CEC, net surface charge and soil-pH$_{(H2O)}$



Biological characteristics

Intense termite activity is, according to some, at least partly accountable for the typical diffuse horizon boundaries of Ferralsols. Termites destroy (remnants of) stratification/rock structure; they increase the depth of the solum and their nests, tunnels and ventilation shafts increase the permeability of the soil. As termites preferentially move fine and medium sized particles and leave coarse sand, gravel and stones behind, they are thought to contribute to *'stoneline'* formation. The depth of the stoneline would then indicate the depth of termite activity.

Note that stonelines may also occur where termites are absent, e.g. formed by soil creep in sloping terrain.

Management and use of Ferralsols

Most Ferralsols have good physical properties. Great soil depth, good permeability and stable microstructure make Ferralsols less susceptible to erosion than most other intensely weathered red tropical soils. Moist Ferralsols are friable and easy to work. They are well drained but may in times be droughty because of their low water storage capacity.

The chemical fertility of Ferralsols is poor; weatherable minerals are absent and cation retention by the mineral soil fraction is weak. Under natural vegetation, nutrient elements that are taken up by the roots are eventually returned to the surface soil with falling leaves and other plant debris. The bulk of all cycling plant nutrients is contained in the biomass; 'available' plant nutrients in the soil (and all living plant roots) are concentrated in the upper 10 to 50 cm soil layer. If the process of *'nutrient cycling'* is interrupted, e.g. after introduction of low input sedentary subsistence farming, the root zone will rapidly become depleted of plant nutrients.

Maintaining soil fertility by manuring, mulching and/or adequate (i.e. long enough) fallow periods and prevention of surface soil erosion are important management requirements.

Strong retention (*'fixing'*) of phosphorus is a problem of Ferralsols (and several other soils, e.g. Andosols). Ferralsols are normally also low in nitrogen, potassium, secondary nutrients (calcium, magnesium, sulphur) and a score of micro-nutrients. Even silica deficiency is possible if silica-demanding crops (e.g. grasses) are grown. Manganese and zinc, which are very soluble at low pH, may at some time reach toxic levels in the soil or become deficient after intense leaching of the soil.

Liming is a means to raise the pH-value of the rooted surface soil. Liming combats aluminium toxicity and raises the CEC. On the other hand, it lowers the AEC, which might lead to collapse of structure elements and slaking at the soil surface. Frequent small doses of lime or basic slag are therefore preferable over one massive application; 0.5 – 2 tons/ha of lime, or dolomite, are normally enough to supply calcium as a nutrient and to buffer the low soil-pH of Ferralsols.

Fertilizer selection and the mode/timing of fertilizer application determine to a great extent the success of agriculture on Ferralsols. Slow-release (rock) phosphate applied at a rate of several tons per hectare eliminates phosphorus deficiency for a number of years. For a quick fix, much more soluble (Double or Triple) Super Phosphate is used, needed in much smaller quantities, especially if placed in the direct vicinity of the roots.

Sedentary subsistence farmers and shifting cultivators on Ferralsols grow a variety of annual and perennial crops. Low volume grazing is also common and considerable areas of Ferralsols are not used for agriculture at all. The good physical properties of Ferralsols and the often level topography would encourage more intensive forms of land use if problems caused by the poor chemical soil properties could be overcome.

ALISOLS (AL)[1]

The Reference Soil Group of the Alisols consists of strongly acid soils with accumulated high activity clays in their subsoils. They occur in humid (sub-)tropical and warm temperate regions, on parent materials that contain a substantial amount of unstable Al-bearing minerals. Ongoing hydrolysis of these minerals releases aluminium, which occupies more than half of the cation exchange sites. Hence, Alisols are unproductive soils under all but acid-tolerant crops. Internationally, Alisols correlate with 'Red Yellow Podzolic Soils' that have high-activity clays (Brazil), 'Ultisols' with high-activity clays (USA, Soil Taxonomy) and with 'Fersialsols' and 'sols fersiallitiques très lessivés (France).

Definition of Alisols[#]

Soils having
1. an *argic*[@] horizon, which has a cation exchange capacity (by 1 M NH_4OAc at pH 7.0) of 24 cmol(+) kg^{-1} clay or more, either starting within 100 cm from the soil surface, or within 200 cm from the soil surface if the argic horizon is overlain by loamy sand or coarser textures throughout, and
2. *alic*[@] properties in most of the layer between 25 and 100 cm from the soil surface, and
3. no diagnostic horizons other than an *ochric*[@], *umbric*[@], *albic*[@], *andic*[@], *ferric*[@], *nitic*[@], *plinthic*[@] or *vertic*[@] horizon.

Common soil units:
Vertic*, Gleyic*, Andic*, Plinthic*, Nitic*, Umbric*, Arenic*, Stagnic*, Abruptic*, Humic*, Albic*, Profondic*, Lamellic*, Ferric*, Skeletic*, Hyperdystric*, Rhodic*, Chromic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Alisols

Connotation: strongly acid soils with subsurface accumulation of high activity clays that have more than 50 percent Al^{3+} saturation; from L. *aluminium*, alum.

Parent material: Alisols can form in a wide variety of parent materials having high-activity clay minerals such as vermiculite or smectite. Most occurrences of Alisols reported so far are on weathering products of basic rocks.

Environment: most common in old land surfaces with a hilly or undulating topography, in humid (sub-)tropical and monsoon climates.

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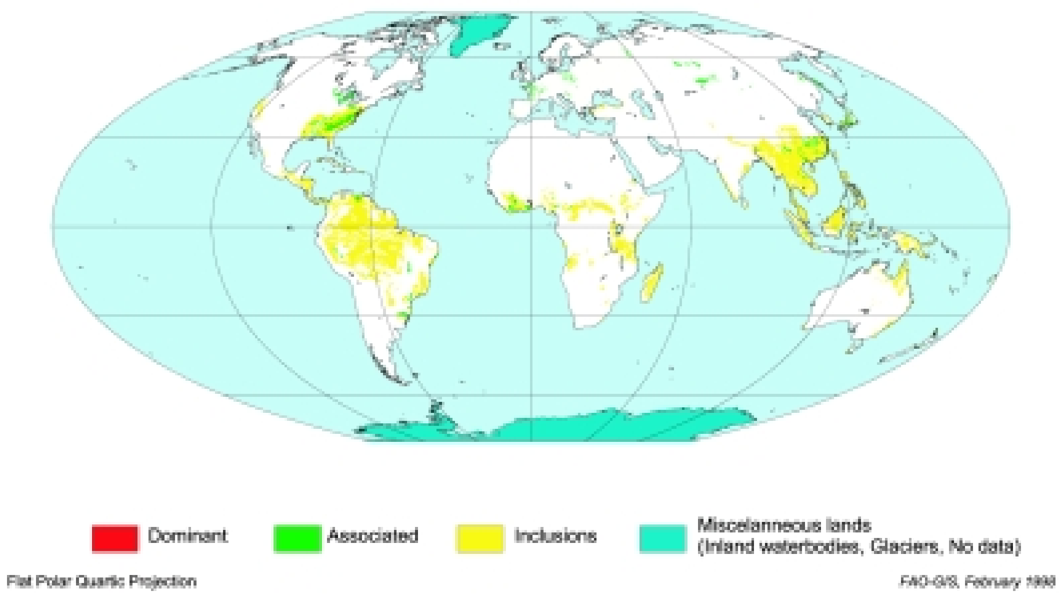
[1] This chapter was contributed by Messrs B. Delvaux and V. Brahy,, Université Catholique de Louvain (UCL), Unité Sciences du Sol, Place Croix du Sud, 2/10 B-1348 Louvain-la-Neuve, Belgium.

Profile development: ABtC profiles. Variations among Alisols are mostly related to truncation of A-horizons in eroded lands.

Use: Alisols contain low levels of plant nutrients (except for Mg^{2+} in some cases) whereas soluble inorganic Al is present in toxic quantities. If liming and full fertilization is no option, use of these soils is generally restricted to crops, which accommodate with low nutrient contents and tolerate high levels of free Al. Alisols are traditionally used in shifting cultivation and for low volume production of undemanding crops. In the past decades, Alisols have increasingly been planted to Al-tolerant estate crops such as tea and rubber, and also to oil palm.

Figure 1
Alisols world-wide



Regional distribution of Alisols

Major occurrences of Alisols are found in Latin America (Ecuador, Nicaragua, Venezuela, Colombia, Peru, Brazil), in the West Indies (Jamaica, Martinique, St. Lucia), in West Africa, the highlands of Eastern Africa, Madagascar and in southeast Asia and northern Australia. See Figure 1. Driessen and Dudal (1991) tentatively estimate that about 100 million ha of these soils are used for agriculture in the tropics.

Alisols occur also in subtropical and Mediterranean regions: they are found in China, Japan and the South Eastern USA and minor occurrences have been reported from around the Mediterranean Sea (Italy, France, and Greece).

Associations with other Reference Soil Groups

Alisols have their argic horizon in common with *Acrisols, Lixisols, Luvisols* and Albeluvisols. They differ from Acrisols and Lixisols because these soils lack high activity clays and from Luvisols because Luvisols lack '*alic'* soil properties. Alisols are less weathered than 'typical red tropical soils' such as *Ferralsols* and *Nitisols*. In the landscape, Alisols can be associated with *Gleysols* and all the Reference Soil Groups mentioned above, except Albeluvisols.

In the humid tropics, Alisols are found on slopes where smectitic saprolithes outcrop; Acrisols or Lixisols and possibly Nitisols or Ferralsols are dominant on plateaux (West Africa, West Indies). Alisols in sloping land can also be seen alongside *Cambisols* (e.g. in the foothills of the Andes). Alisol-Acrisol patterns in flat and level terrain reflect the lithological composition of the dominant parent material (Amazon region, Colombia).

In tropical and subtropical regions with distinct wet and dry seasons, Alisols occur alongside Luvisols in sloping areas and together with *Vertisols* (Kenya, Somalia) or Gleysols (Southeast USA) in depression areas. Alisols in regions with warm, wet summers and cold, dry winters are associated with Cambisols, notably on eroding steep slopes in hilly areas (South Eastern China).

In Mediterranean areas, Alisols have been found in old river terraces; their occurrence is probably associated with wetter climate conditions in a distant past. Alisols may also occur on slopes that are exposed to frequent rain bearing winds.

Genesis of Alisols

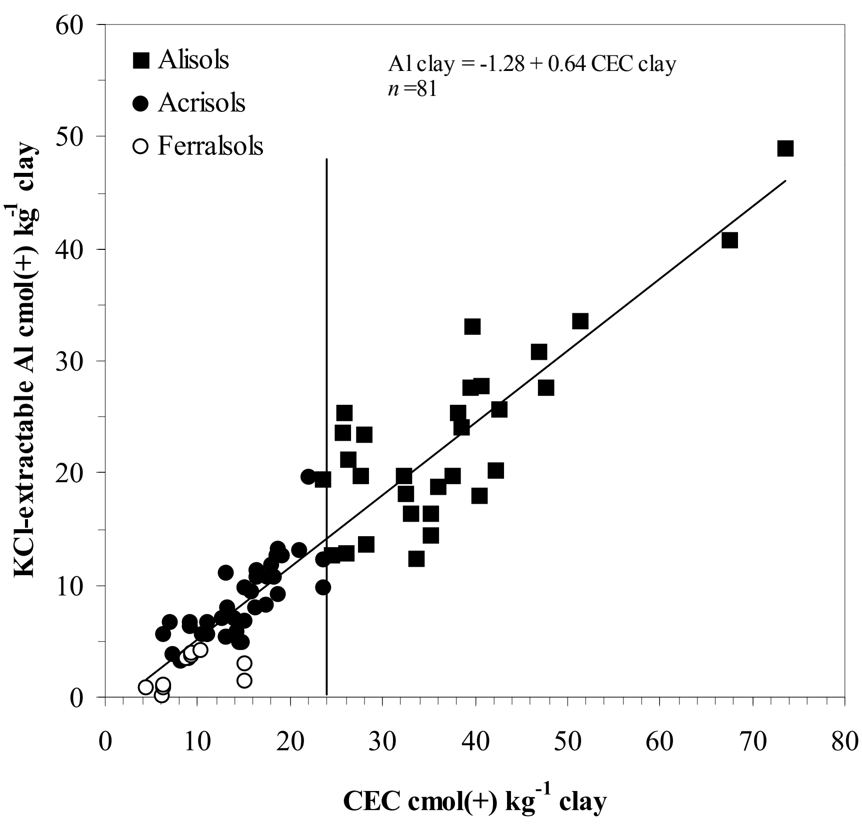
Alisols form where ongoing hydrolysis of secondary high-activity clay minerals such as vermiculite and smectite releases much aluminium. In practice, Alisol formation is confined to environments where most weatherable primary minerals have disappeared and secondary high-activity clays dominate the clay complex. Where these materials outcrop, for instance in hilly topography, the secondary high-activity minerals weather under humid conditions with intense leaching of silica and alkaline and alkaline-earth cations. Alisol formation involves three distinct steps:

1. The *first step* is transformation and/or hydrolysis of primary weatherable minerals in the parent rock and moderate leaching of silica. These processes produce a saprolith with little weatherable primary minerals and a dominance of secondary high-activity clays formed by transformation of micas. The high-activity clays are predominantly smectitic on basic and intermediate rocks, e.g. basalt and andesite, and vermiculitic on more siliceous rocks such as granite, gneiss and schist.
2. The *second step* involves redistribution of clay in the soil and accumulation in an *argic* horizon. Such redistribution can be vertical migration of clay particles (clay illuviation) and/or lateral clay transport. *Note that* fine clay particles can move only under mildly acid conditions, say in the pH range from pH 5 to pH 6.5. At lower pH, Al^{3+}-ions become dominant on the exchange complex. Al-saturation may then keep the clay flocculated and impede dispersion. This prompted some authors to suggest that argic horizons in strongly weathered soils in the wet tropics are relics from earlier soil genesis involving clay illuviation. Textural differentiation could also have been brought about by lateral transport of clay and/or by weathering of clay in the topsoil; this latter process seems to be prominent in most Alisols. *Note also that* many Alisols on slopes in (sub)tropical areas became truncated; former *subsoil* horizons with clay illuviation are now exposed at the soil surface.

3. The *third step* involves weathering of secondary high-activity clay; this step may overlap with clay redistribution as described above. High-activity clays are unstable in environments that are depleted of silica and alkaline and alkaline earth cations. Their weathering liberates soluble aluminium and - on basic parent materials - iron and magnesium from the octahedral inner layers of (2:1) clay minerals. Iron oxides account for the reddish colour of some Alisols, e.g. the Rhodic Alisols of the Caribbean region.

Figure 2 shows the relation between KCl-extractable Al and the cation exchange capacity (CEC), both expressed in cmol(+) kg^{-1} clay. The data were collected from ferralic and argic subsurface horizons in acid (pH_{KCl} < 4.0) Ferralsols, Acrisols and Alisols from Indonesia, the Caribbean region, Rwanda, Cameroon, Peru and Colombia.

Figure 2
Consistent, strong and positive correlation of KCl-extractable Al and CEC-clay is found in acid Ferralsols, Acrisols and Alisols from all over the world



The correlation of KCl-extractable Al and CECclay documented by Figure 2 supports the following statements.

1. Weathering clay minerals determine the content of KCl-extractable aluminium in strongly weathered acid soils in the (sub-)tropics. Consequently the hazard of Al-toxicity increases from acid Ferralsols to Acrisols and Alisols. Low pH-KCl values have implications in terms of Al-saturation that differ by soil type.

2. The exchange properties of the clay fraction (CECclay) reflect the content of high activity clays and are a useful indicator of the degree of soil weathering.
3. Exceptionally high levels of KCl-extractable Al (= 12 cmol(+) kg^{-1} clay) occur in Alisols; this sets them apart from strongly acid Ferralsols and Acrisols.

Weathering processes affect the clay mineralogy of soils; the mineral assemblage of Alisols appears to be in a state of transition from 'bisiallitic' high-activity clays to 'fermonosiallitic' material that is rich in iron oxides and kaolinite. The content of iron oxides is largely dictated by the composition of the parent rock, notably its content of primary ferromagnesium silicates. The transitional character of Alisol clay mineralogy is further evidenced by:

- *kaolinite-smectite mixed-layer clay minerals* found in some Rhodic Alisols (West Indies, Kalimantan);
- *Al-hydroxy-interlayered smectite and vermiculite* found in some Haplic Alisols (China) and in Rhodic Alisols (West Indies).

Al-hydroxy-interlayered 2:1 clay minerals resemble the mineralogical structure of 1:1 clay minerals in the sense that their structure is of the 1:1:1:1 type, with alternating octahedral and tetrahedral sheets. Their stability in soil environments is indeed similar to that of kaolinite.

Figure 3
KCl-extractable Al and/or [KCl-extractable Al + exchangeable Mg] correlate with CECclay in tropical soils with pH-KCl values less than 4.0

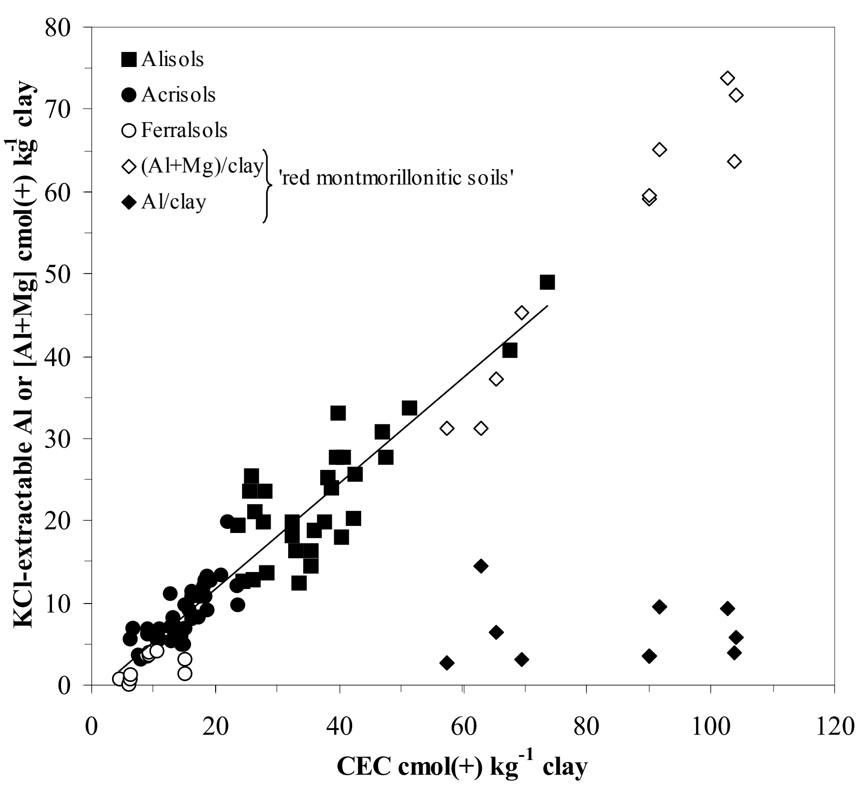


Figure 3 illustrates also how release of octahedral Al from 2:1 layer silicates contributes to the development of *alic* soil properties. Figure 3 is an extended version of Figure 2; it considers additional data from strongly acid soils with smectites. These acid soils developed in weathering material of basic rock and are rich in octahedral Mg. The 'red montmorillonitic soils' (from Martinique) contain much smectite clay and free iron oxides (hematite) and are red indeed: Munsell hues of 2.5 YR and 10R are common. They contain less than 12 cmol(+) KCl-extractable Al per kg clay even though the CEC-clay exceeds 55 cmol(+) kg^{-1}. However, the relation between (Al + Mg) and CEC-clay produced the strong positive correlation of Figure 2. This suggests that Al and Mg released from weathering high-activity clay caused saturation of the exchange complex in these soils. *Note that* strongly acid soils with considerable Mg-saturation are not Alisols; they would rather key out as Eutric Cambisols.

Alic soil properties may have an impact on the transformation of humus. It was observed in forest areas with Alisols in Kalimantan (Indonesia) that humus readily accumulates, possibly because biological activity is retarded by Al having a toxic effect on soil organisms.

Characteristics of Alisols

Morphological characteristics

Most Alisols have an *ochric* surface horizon but darker *umbric* horizons can be expected under forest. Soil structure is rather weak in the surface horizon because biological activity is hindered by the strong acidity. The surface horizon overlies a dense *argic* subsurface horizon that may hinder deep percolation of water. The structure of the argic horizon is clearly more stable than that of the surface soil. The expression of soil structure varies between soils with the relative contents of high-activity clays and free iron.

Mineralogical characteristics

Secondary clay minerals dominate the mineral assemblage of Alisols. *Note however that* the proportions of low- and high-activity clays vary between soils or between soil horizons because the clay is in a state of transition. Weathering high-activity clays release considerable quantities of Al; at the same time the content of kaolinite increases and CEC decreases. Strong adsorption of Al^{3+} by high-activity clays counteracts the formation of gibbsite ($Al_2O_3.3H_2O$). The content of free iron oxides varies between Alisols depending on the nature and weathering stage of the parent material. The sand fraction consists of (weathering-resistant) quartz and the silt content is small.

Physical characteristics

The physical characteristics of Alisols are directly related to the relative contents of high-activity clays, low-activity clays and iron oxides. Where swelling and shrinking clays dominate the mineral assemblage, specific physical features may develop that resemble elements of *'vertic'* horizons. Telltale signs are: distinct cracks, rapid bypass flow of water in dry soil and slow infiltration of water in wet soil, shining faces of structural peds, prismatic structure elements in the subsurface horizon and generally few macro-pores. Such Alisols have CEC-clay values in excess of above 50 cmol(+) kg^{-1}. Alisols in weathering materials from basic rock tend to have more iron oxides and more stable structures, particularly in the subsurface horizon.

In many Alisols, textural differentiation between surface and subsurface horizons imparts different physical properties. Surface horizons tend to have an unstable structure (slaking!) and reduced permeability, in particular where the subsurface horizon is dense and massive as is the case in Alisols that have relatively low contents of high activity clays and iron oxides. This restricts internal soil drainage and increases the danger of erosion in sloping lands. In cropped lands, the low level of biological activity, a direct consequence of the acid and nutrient-poor environment, further enhances the adverse physical properties of the surface horizon.

Chemical characteristics

Ongoing weathering of high-activity, Al-bearing clay leads to severe chemical infertility: Al and possibly Mn are present in toxic quantities whereas levels of other plant nutrients are low and unbalanced. However, the favourable cation exchange properties make some Alisols productive under intensive management with adequate liming and application of manure and fertilizers. The mineral reserves of Alisols are conditioned by the clay fraction and depend largely on the composition of high-activity clays that act as weatherable minerals in the system. In most Alisols, these reserves are low in Ca and K. Low pH and presence of large quantities of iron oxide are conducive to P-immobilization but much less than in Acrisols and Ferralsols. The organic matter content of cultivated Alisols is usually modest, in contrast with Alisols under natural forest.

Management and use of Alisols

Alisols occur predominantly on old land surfaces with hilly or undulating topography. The generally unstable surface soil of cultivated Alisols makes them susceptible to erosion; truncated soils are quite common. Toxic levels of aluminium at shallow depth and poor natural soil fertility are added constraints. As a consequence, many Alisols allow only cultivation of shallow-rooting crops and these suffer from drought stress during the dry season. By and large, Alisols are unproductive soils. Their use is generally restricted to acidity-tolerant crops or low volume grazing. The productivity of Alisols in subsistence agriculture is generally low as these soils have a limited capacity to recover from chemical exhaustion. If fully limed and fertilized, crops on Alisols may benefit from the considerable cation exchange capacity and rather good water holding capacity. Alisols are increasingly planted to aluminium-tolerant estate crops such tea and rubber but also to oil palm and in places to coffee and sugar cane.

NITISOLS (NT)

The Reference Soil Group of the Nitisols accommodates deep, well-drained, red, tropical soils with diffuse horizon boundaries and a subsurface horizon with more than 30 percent clay and moderate to strong angular blocky structure elements that easily fall apart into characteristic shiny, polyhedric ('nutty') elements. Nitisols are strongly weathered soils but far more productive than most other red tropical soils. Nitisols correlate with 'Terra roxa estruturada' (Brazil), kandic groups of Alfisols and Ultisols (Soil Taxonomy, USA), 'Sols Fersialitiques' or 'Ferrisols' (France) and with the 'Red Earths'.

Definition of Nitisols[#]

Soils,
1. having a *nitic*[@] horizon starting within 100 cm from the soil surface, and
2. having gradual to diffuse horizon boundaries, and
3. lacking a *ferric*[@], *plinthic*[@] or *vertic*[@] horizon within 100 cm from the soil surface.

Common soil units:
Andic*, Ferralic*, Mollic*, Alic*, Umbric*, Humic*, Vetic*, Alumic*, Dystric*, Eutric*, Rhodic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Nitisols

Connotation: deep, red, well-drained tropical soils with a clayey *'nitic'* subsurface horizon that has typical 'nutty', polyhedric, blocky structure elements with shiny ped faces; from L. *nitidus*, shiny.

Parent material: finely textured weathering products of intermediate to basic parent rock, possibly rejuvenated by recent admixtures of volcanic ash. The clay assemblage of Nitisols is dominated by kaolinite/(meta)halloysite. Nitisols are rich in iron and have little water-dispersible ('natural') clay.

Environment: Nitisols are predominantly found in level to hilly land under tropical rain forest or savannah vegetation.

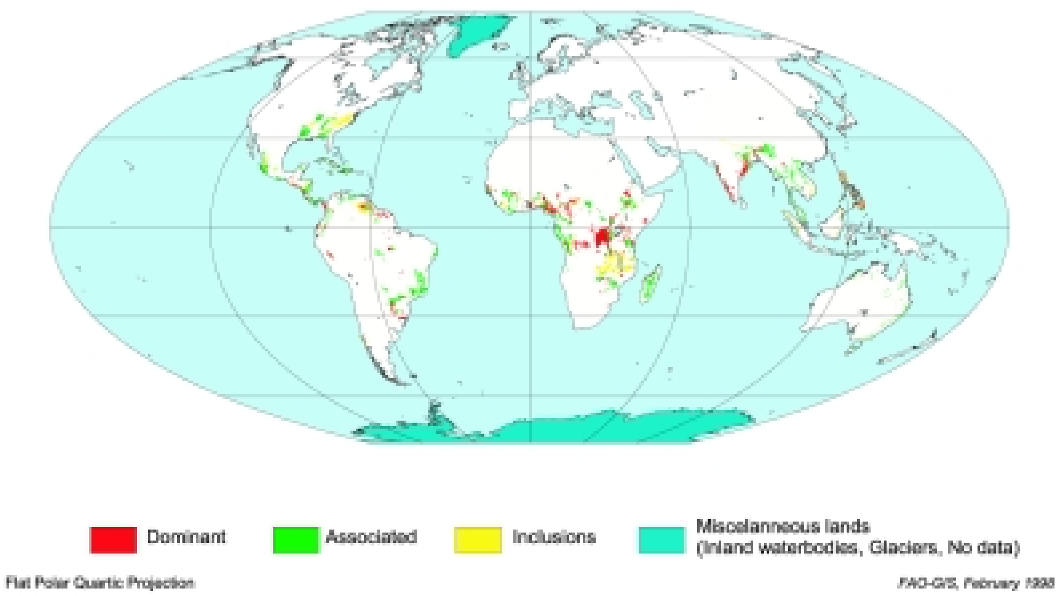
Profile development: AB(t)C-profiles. Red or reddish brown clayey soils with a *'nitic'* subsurface horizon of high aggregate stability.

Use: Nitisols are planted to farm and plantation crops. They are generally considered to be 'fertile' soils in spite of their low level of 'available' phosphorus and their normally low base status. Nitisols are deep, stable soils with favourable physical properties.

Regional distribution of Nitisols

There are approximately 200 million hectares of Nitisols world-wide. More than half of all Nitisols are found in tropical Africa, notably in the highlands (>1000 m.) of Ethiopia, Kenya, Congo and Cameroon. Elsewhere, Nitisols are well represented at lower altitudes, e.g. in tropical Asia, South America, Central America and Australia. See Figure 1.

Figure 1
Nitisols world-wide

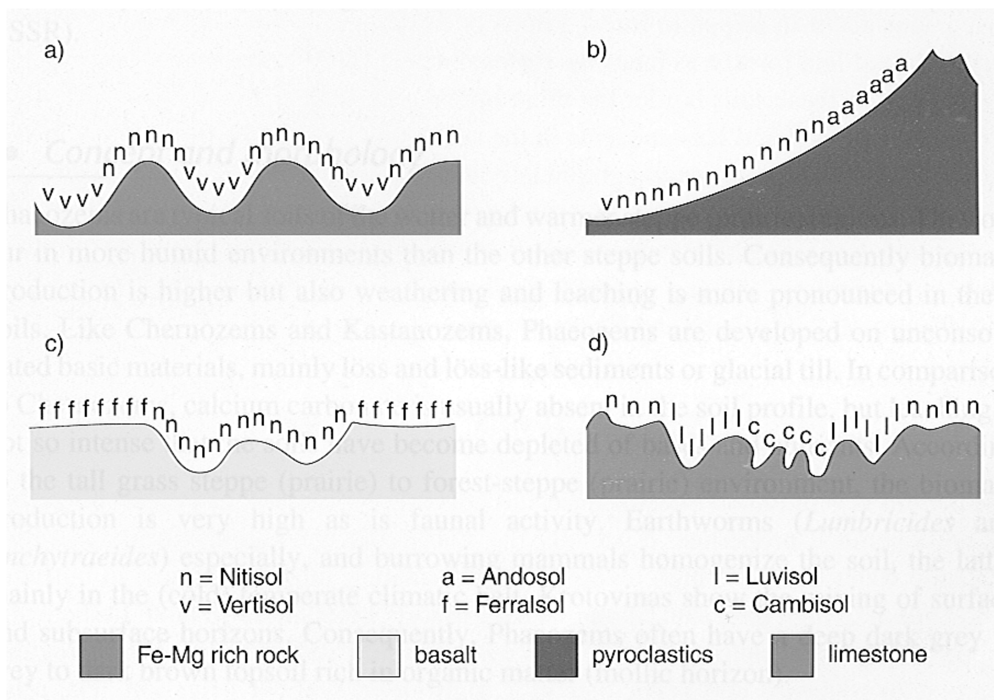


Associations with other Reference Soil Groups

Relationships between Nitisols and other Reference Soil Groups are quite diverse because they are conditioned by a score of (localized) factors. Figure 2 presents common lateral linkages.

1. In *undulating landscapes*, Nitisols are mostly found on basic and ultra-basic rock types in upper and middle slope positions; they grade into Vertisols or vertic units of other Reference Soil Groups towards lower slope sections and/or bottom lands.
2. In *volcanic landscapes,* Nitisols occur in mid-slope positions, between Andosols at higher elevation and more profoundly weathered 'red tropical soils' on lower slope sections.
3. In *uplifted and dissected landscapes* on old surfaces, Nitisols are found on slopes in association with Ferralsols on flat and level plateaux.
4. In *landscapes on limestone,* Nitisols occur in pockets, in association with reddish soils such as Chromic Cambisols and Luvisols.

Figure 2
Some common lateral linkages between Nitisols and other Reference Soil Groups



Genesis of Nitisols

Nitisol formation involves the following processes:

1. *'ferralitization'*, i.e. intensive hydrolysis of weathering minerals combined with leaching of silica and bases, and relative accumulation of (meta)halloysite, kaolinite and sesquioxides. The process is the same as described for Ferralsols but it is still in an early stage.
2. *'nitidization'*, i.e. formation of strongly angular, shiny peds in the nitic subsurface horizon. Nitidization is probably the result of alternating micro-swelling and shrinking and produces well-defined structural elements with strong, shiny pressure faces.
3. *'homogenization'* of the soil by termites, ants, worms and other soil fauna (*'biological pedoturbation'*). This process is particularly prominent in the top 100-cm soil layer where it results in a crumb and/or subangular blocky soil structure and gradual or diffuse soil horizon boundaries.

Characteristics of Nitisols

Morphological characteristics

Nitisols are normally deeper than 150 cm and dusky red or dark red in colour. They are well-drained soils with a clayey subsurface horizon that is deeply stretched and has nutty or polyhedric blocky structure elements with shiny ped faces. Reticular manganese segregation on ped faces is common in the lower parts of the *'nitic'* subsurface horizon. The relative decrease of the clay content of the nitic horizon is gradual (less than 20 percent from its maximum at 150 cm below the surface). Horizon boundaries are typically gradual or diffuse. Laterally, the nitic horizon may wedge out or decrease in thickness, or dip below a ferralic or argic horizon. It may replace either one of these or change into a cambic horizon. It also may acquire properties found in vertic or ferric horizons. Such lateral transitions are gradual and hardly perceptible within distances of 5 to 10 metres.

Mineralogical characteristics

The clay assemblage of Nitisols is dominated by kaolinite and (meta)halloysite. Minor quantities of illite, chloritized vermiculite and randomly interstratified clay minerals may be present, alongside hematite, goethite and gibbsite. Nitisols contain 4.0 percent or more 'free' iron (Fe_2O_3 by dithionite-citrate extraction) in the fine earth fraction and more than 0.2 percent 'active' iron (by acid oxalate extraction at pH 3). The ratio of 'active' to 'free' iron is 0.05 or more. The mineralogical composition of the sand fraction depends strongly on the nature of the parent material. Although weathering-resistant minerals (notably quartz) predominate, minor quantities of more easily weathering minerals, e.g. feldspars, volcanic glass, apatite, or amphiboles, may (still) be present indicating that Nitisols are less strongly weathered than associated Ferralsols.

Hydrological characteristics

Nitisols are free-draining soils and permeable to water (50–60 percent pores). Their retention of 'plant-available' moisture is only fair (5-15 percent by volume) but their total moisture storage is nonetheless satisfactory because the rootable soil layer extends to great depth, commonly deeper than 2 m.. Most Nitisols can be tilled within 24 hours after wetting without serious deterioration of the soil structure.

Physical characteristics

Nitisols are hard when dry, very friable to firm when moist and sticky and plastic when wet. Gravel or stones are rare but fine iron-manganese concretions (*'shot'*) may be present.

Chemical characteristics

The cation exchange capacity of Nitisols is high if compared to that of other tropical soils such as Ferralsols, Lixisols and Acrisols. The reasons are:

1. Although the clay assemblage is dominated by low-activity clays, the *clay content is high* (more than 30 percent and not seldom more than 60 percent), *and*
2. *Soil organic matter* makes a considerable contribution to the overall CEC, especially in mollic or umbric soil units.

Base saturation varies from less than 10 to more than 90 percent. The soil-$pH_{(H2O)}$ is typically between 5.0 and 6.5; P-fixation is considerable but acute P-deficiency is rare.

Biological characteristics

Intense faunal activity is accountable for the typical gradual horizon boundaries of Nitisols. Termites are particularly effective in homogenizing soil; volcanic glass deposited on the (present) surface was found back at a depth of 7 meters in Nitisols in Kenya.

Management and use of Nitisols

Nitisols are among the most productive soils of the humid tropics. The deep and porous solum and the stable soil structure of Nitisols permit deep rooting and make these soils quite resistant to erosion. The good workability of Nitisols, their good internal drainage and fair water holding properties are complemented by chemical (fertility) properties that compare favourably to those of most other tropical soils. Nitisols have relatively high contents of weathering minerals and surface soils may contain several percent of organic matter, in particular under forest or tree crops. Nitisols are planted to plantation crops such as cocoa, coffee, rubber and pineapple, and are also widely used for food crop production on smallholdings. High P-sorption calls for application of P-fertilizer, usually provided as slow release, low-grade 'rock phosphate' (several tons/ha with maintenance doses every few years) in combination with smaller applications of better soluble 'super phosphate' for short-term response by the crop.

ACRISOLS (AC)

The Reference Soil Group of the Acrisols holds soils that are characterized by accumulation of low activity clays in an *argic* subsurface horizon and by a low base saturation level. Acrisols correlate with 'Red-Yellow Podzolic soils' (e.g. Indonesia), 'Podzolicos vermelho-amarello distroficos a argila de atividade baixa' (Brazil), 'Sols ferralitiques fortement ou moyennement désaturés' (France), 'Red and Yellow Earths' and with several subgroups of Alfisols and Ultisols (Soil Taxonomy, USA).

Definition of Acrisols[#]

Soils,

1. having an *argic* horizon, which has a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) of less than 24 cmol(+) kg^{-1} clay in some part, either starting within 100 cm from the soil surface, or within 200 cm from the soil surface if the argic horizon is overlain by loamy sand or coarser textures throughout, and
2. having less than 50 percent base saturation (in 1M NH_4OAc at pH 7.0) in the major part between 25 and 100 cm.

Common soil units:

Leptic*, Gleyic*, Vitric*, Andic*, Plinthic*, Umbric*, Arenic*, Stagnic*, Abruptic*, Geric*, Humic*, Albic*, Profondic*, Lamellic*, Ferric*, Hyperochric*, Skeletic*, Vetic*, Alumic*, Hyperdystric*, Rhodic*, Chromic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Acrisols

Connotation: strongly weathered acid soils with low base saturation; from L. *acris*, very acid.

Parent material: most extensive on acid rock weathering, notably in strongly weathered clays, which are undergoing further degradation.

Environment: mostly old land surfaces with hilly or undulating topography, in regions with a wet tropical/monsoonal, subtropical or warm temperate climate. Light forest is the natural vegetation type.

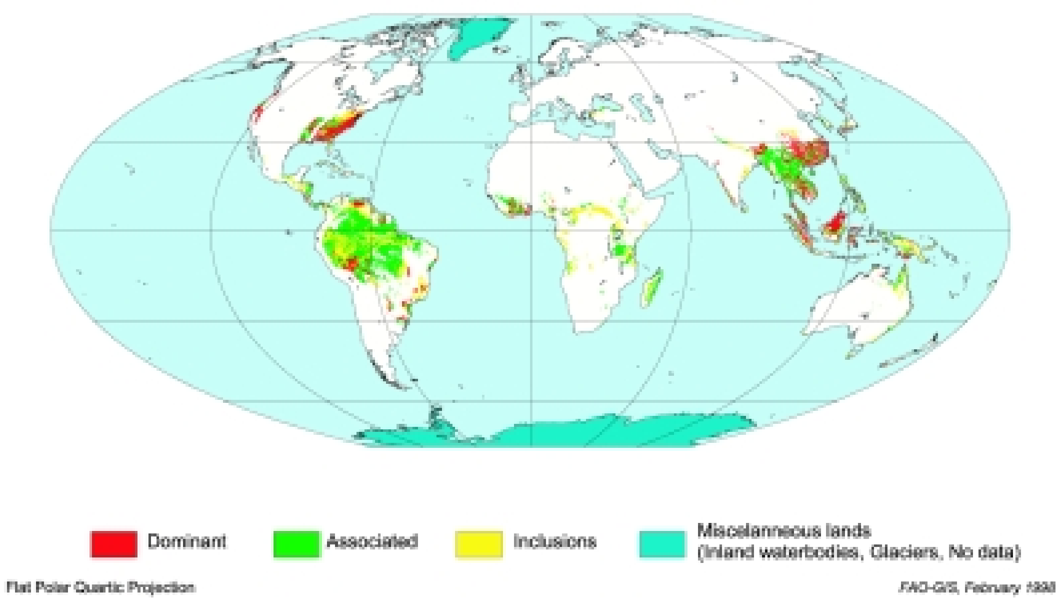
Profile development: AEBtC-profiles. Variations in Acrisols will normally correlate with variations in terrain conditions (drainage, seepage). A shallow A-horizon with dark, raw and acid organic matter grades into a yellowish E-horizon. The underlying argic Bt-horizon has stronger reddish or yellowish colour than the E-horizon.

Use: a general paucity of plant nutrients, aluminium toxicity, strong phosphorus sorption, slaking/crusting and high susceptibility to erosion impose severe restrictions on arable land uses. Large areas of Acrisols are used for subsistence farming, partly in a system of shifting cultivation. By and large, Acrisols are not very productive soils; they perform best under undemanding, acidity-tolerant crops such as pineapple, cashew, oil palm or rubber.

Regional distribution of Acrisols

Acrisols are found on acid rocks, mostly of Pleistocene age or older. They are most extensive in Southeast Asia, the southern fringes of the Amazon Basin, the southeastern USA and in both east and west Africa. There are approximately 1000 million hectares of Acrisols world-wide. See Figure 1.

Figure 1
Acrisols world-wide



Associations with other Reference Soil Groups

Acrisols are often the dominant soil group on old erosional or depositional surfaces and in piedmont areas in humic tropical regions where they are associated and alternating with *Nitisols, Ferralsols* and *Lixisols.* Acrisols are also well represented on ancient shield landscapes in the humid tropics, often alongside Ferralsols in less eroded, flatter areas or in areas that receive weathering material from adjacent uplands. A typical setting would have Acrisols on the eroding slopes of low hills and Ferralsols on nearby stable pediments or uplands. In mountain areas, Acrisols can be found on stable ridge tops, with *Regosols* and *Cambisols* on steeper and less stable slopes. In valleys, Acrisols are to be expected on the higher terraces with *Luvisols* or Cambisols on lower terraces. Old alluvial fans in the humid tropics may have Acrisols on higher parts with Plinthosols in adjacent depression areas.

Genesis of Acrisols

Acrisols are characterized by their argic B-horizon, dominance of stable low activity clays and general paucity of bases. Formation of an *argic* illuviation horizon involves

1. *clay dispersion*
2. *clay transport*, and
3. *clay accumulation* in a subsurface horizon.

These processes are discussed in some detail in the chapter on Luvisols. *Note that* some authors dismiss all clay illuviation horizons in highly weathered soils in the wet tropics as relics from a distant past.

The process of *'ferralitization'* by which sesquioxides accumulate in the soil profile as a result of advanced hydrolysis of weatherable primary minerals was discussed in the chapter on Ferralsols. Subsequent redistribution of iron compounds by *'cheluviation'* and *'chilluviation'* (see under Podzols) is accountable for colour differentiation directly under the A(h)-horizon where an eluviation horizon with yellowish colours overlies a more reddish coloured Bst-horizon (hence the name 'Red-Yellow Podzolics' as used e.g. in southeast Asia).

Characteristics of Acrisols

Morphological characteristics

Most Acrisols have a thin, brown, *ochric* surface horizon, particularly in regions with pronounced dry seasons; darker colours are found where (periodic) waterlogging retards mineralization of soil organic matter. The underlying *albic* subsurface horizon has weakly developed structure elements and may even be massive; it is normally whitish to yellow and overlies a stronger coloured yellow to red *argic* subsurface horizon. The structure of this sesquioxide-rich illuviation horizon is more stable than that of the eluviation horizon. *Gleyic soil properties* and/or *plinthite* are common in Acrisols in low terrain positions.

Mineralogical characteristics

Acrisols have little weatherable minerals left. The contents of Fe-, Al- and Ti-oxides are comparable to those of Ferralsols or somewhat lower; the SiO_2/Al_2O_3 ratio is 2 or less. The clay fraction consists almost entirely of well-crystallized kaolinite and some gibbsite.

Hydrological characteristics

Acrisols under a protective forest cover have porous surface soils. If the forest is cleared, the valuable A-horizon degrades and slakes to form a hard surface crust. The crust allows insufficient penetration of water during rain showers with devastating surface erosion (low structure stability!) as an inevitable consequence. Many Acrisols in low landscape positions show signs of periodic water saturation; their surface horizons are almost black whereas matrix colours are close to white in the eluvial albic horizon.

Physical characteristics

Most Acrisols have weak microstructure and massive macrostructure, especially in the surface and shallow subsurface soil that have become depleted of sesquioxides. Bonding between sesquioxides and negatively charged low activity clays is less strong than in Ferralsols. Consequently, the ratio of water-dispersible '*natural clay'* over *'total clay'* (see under Ferralsols) is higher than in Ferralsols.

Chemical characteristics

Acrisols have poor chemical properties. Levels of plant nutrients are low and aluminium toxicity and P-sorption are strong limitations. As biological activity is low in Acrisols, natural regeneration, e.g. of surface soil that was degraded by mechanical operations, is very slow.

Management and use of Acrisols

Preservation of the surface soil with its all-important organic matter is a precondition for farming on Acrisols. Mechanical clearing of natural forest by extraction of root balls and filling of the holes with surrounding surface soil produces land that is largely sterile because toxic levels of aluminium (the former subsoil) kill any seedlings planted outside the filled-in spots.

Adapted cropping systems with complete fertilization and careful management are required if sedentary farming is to be practiced on Acrisols. The widely used '*slash and burn'* agriculture ('shifting cultivation') may seem primitive at first sight but is really a well adapted form of land use, developed over centuries of trial and error. If occupation periods are short (one or a few years only) and followed by a sufficiently long regeneration period (up to several decades), this system probably makes the best use of the limited resources of Acrisols.

Low-input farming on Acrisols is not very rewarding. Undemanding, acidity-tolerant cash crops such as pineapple, cashew or rubber can be grown with some success. Increasing areas of Acrisols are planted to oil palm (e.g. in Malaysia and on Sumatra). Large areas of Acrisols are (still) under forest, ranging from high, dense rain forest to open woodland. Most of the tree roots are concentrated in the humous surface horizon with only few tap roots extending down into the subsoil. In South America, Acrisols are also found under savannah. Acrisols are suitable for production of rain-fed and irrigated crops only after liming and full fertilization. Rotation of annual crops with improved pasture maintains the organic matter content.

LIXISOLS (LX)

The Reference Soil Group of the Lixisols consists of strongly weathered soils in which clay has washed out of an eluvial horizon (L. *lixivia* is washed-out substances) down to an *argic* subsurface horizon that has low activity clays and a moderate to high base saturation level. Lixisols were formerly included in the 'Red-Yellow Podzolic soils' (e.g. Indonesia), 'Podzolicos vermelho-amarello eutroficos a argila de atividade baixa' (Brazil), 'Sols ferralitiques faiblement désaturés appauvris' and 'Sols ferrugineux tropicaux lessivés' (France), 'Red and Yellow Earths', 'Latosols' or classified as oxic subgroups of Alfisols (Soil Taxonomy, USA).

Definition of Lixisols[#]

Soils,
having an *argic* horizon starting within 100cm from the soil surface, or within 200 cm from the soil surface if the argic horizon is overlain by loamy sand or coarser textures throughout.

Common soil units:
Leptic*, Gleyic*, Vitric*, Andic*, Plinthic*, Calcic*, Arenic*, Geric*, Stagnic*, Abruptic*, Humic*, Albic*, Profondic*, Lamellic*, Ferric*, Hyperochric*, Vetic*, Rhodic*, Chromic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Lixisols

Connotation: strongly weathered soils in which clay is washed down from the surface soil to an accumulation horizon at some depth; from L. *lixivia*, washed-out substances.

Parent material: unconsolidated, strongly weathered and strongly leached, finely textured materials.

Environment: regions with a tropical, subtropical or warm temperate climate with a pronounced dry season, notably on old erosional or depositional surfaces. Many Lixisols are (surmised to be) polygenetic soils with characteristics formed under a more humid climate in the past.

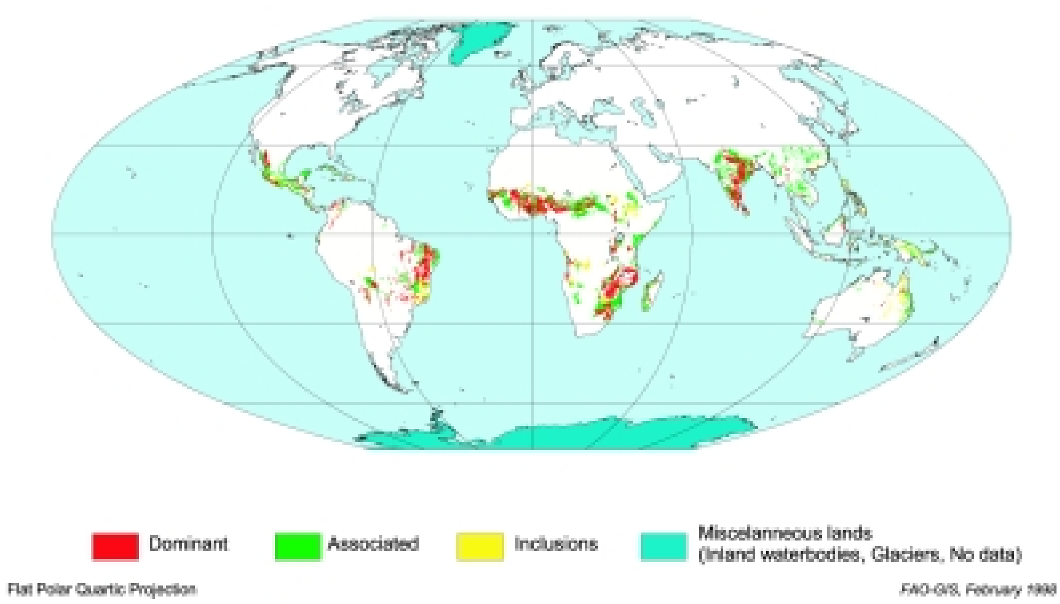
Profile development: ABtC-profiles. On slopes and on other surfaces subject to erosion, the argic accumulation horizon may be exposed or at shallow depth.

Use: most 'unreclaimed' Lixisols are under savannah or open woodland vegetation. Such areas are often used for low volume grazing. Perennial crops or forestry are suitable land uses; arable farming requires recurrent inputs of fertilizers and/or lime. The unstable surface soil structure makes Lixisols prone to slaking and erosion in sloping land.

Regional distribution of Lixisols

Lixisols are found in seasonally dry tropical, subtropical and warm temperate regions, on Pleistocene and older surfaces. These soils cover a total area of about 435 million hectares, of which more than half in Sub-Sahelian and East Africa, about one quarter in South and Central America and the remainder on the Indian subcontinent and in southeast Asia and Australia. As Lixisols are a recent introduction in soil classification, their total extent is not accurately known. See Figure 1.

Figure 1
Lixisols world-wide



Associations with other Reference Soil Groups

Lixisols are found together with other soils that have an *argic* subsurface horizon such as *Alisols, Acrisols* and *Luvisols.* Differences between these Reference Soil Groups and Lixisols are entirely based on analytical properties and separation may be problematic in the field. The situation is further complicated by the fact that most Lixisols are probably polygenetic; they are particularly well represented on old erosional or depositional surfaces where arid and humid periods have alternated in Pleistocene times. Lixisols in areas with basic rocks occur together with *Nitisols* or with *Vertisols, Planosols, Plinthosols* and *Gleysols* in depression areas and on plains. Lixisols in ancient shield areas in the wet tropics are found together with *Ferralsols*, generally with Lixisols on slopes and other surfaces that are subject to erosion and Ferralsols in flatter, less erodable terrain. Lixisols in valleys are mostly restricted to the higher (= older) terraces whereas lower terraces have Luvisols or Cambisols. Lixisols on old alluvial fans in tropical regions can occur alongside *Plinthosols* in wet depression areas.

Genesis of Lixisols

It is widely felt that (many) Lixisols started their development under a wetter climate than the present. Strong weathering during the early stages of soil formation could have been followed by chemical enrichment in more recent times, i.e. after the climate had changed towards an annual evaporation surplus. Fossil *plinthite* and/or coarse reddish mottles or indurate iron nodules in the subsurface soil of many Lixisols also hint at wetter conditions in the past. There are indications that base-rich aeolian deposits enriched (some) Lixisols whereas others could have been improved by biological activity (import of bases from the deeper subsoil) or by lateral seepage of water. The reddish or yellow colours of many Lixisols (notably in argic horizons) are the result of *'rubefaction'* brought about by dehydration of iron compounds in long dry seasons.

Characteristics of Acrisols

Morphological characteristics

Most Lixisols have a thin, brown, *ochric* surface horizon over a brown or reddish brown *argic* Bt-horizon that often lacks clear evidence of clay illuviation other than a sharp increase in clay content over a short vertical distance. The argic horizon has a somewhat stronger structure than normally observed in Acrisols (higher base saturation!). The overlying eluvial E-horizon, when still present, is commonly massive and very hard when dry (referred to as *'hard setting'*). Stone lines are not uncommon in the subsoil.

Mineralogical characteristics

Advanced weathering is commensurate with a low silt-to-clay ratio, dominance of 1:1 clays (leaching of silica) and higher Fe-, Al- and Ti-oxide contents than are normal in less weathered soils. The SiO_2/Al_2O_3 ratio of Lixisol material is 2 or less; gibbsite contents are only slightly below those found in most Ferralsols.

Hydrological characteristics

Most Lixisols are free-draining and lack evidence of water saturation. However, Lixisols with redoximorphic features in the upper metre of the profile are not rare; they are either Stagnic Lixisols that show evidence of a perched water table (above the argic B-horizon) in periods of wetness or Gleyic Lixisols in depression areas with shallow groundwater.

Physical characteristics

Lixisols have higher base saturation and accordingly somewhat stronger structure than normally found in Acrisols but slaking and caking of the surface soil are still serious problems. The moisture holding properties of Lixisols are slightly better than of Ferralsols or Acrisols with the same contents of clay and organic matter.

Chemical characteristics

Lixisols are strongly weathered soils with low levels of available nutrients and low nutrient reserves. However the chemical properties of Lixisols are generally better than of Ferralsols and Acrisols because of their higher soil-pH and the absence of serious Al-toxicity. The absolute amount of exchangeable bases is generally not more than 2 cmol(+) kg^{-1} fine earth on account of the low cation exchange capacity of Lixisols.

Management and use of Lixisols

Areas with Lixisols that are still under natural savannah or open woodland vegetation are widely used for low volume grazing. Preservation of the surface soil with its all-important organic matter is of utmost importance. Degraded surface soils have low aggregate stability and are prone to slaking and/or erosion if exposed to the direct impact of raindrops. Tillage of wet soil or use of (too) heavy machinery will compact the soil and cause serious structure deterioration. Tillage and erosion control measures such as terracing, contour ploughing, mulching and use of cover crops help to conserve the soil. The low absolute level of plant nutrients and the low cation retention by Lixisols makes recurrent inputs of fertilizers and/or lime a precondition for continuous cultivation. Chemically and/or physically deteriorated Lixisols regenerate very slowly if not actively reclaimed.

By and large, perennial crops are to be preferred over annual crops, particularly on sloping land. Cultivation of tuber crops (cassava, sweet potato) or groundnut increases the danger of soil deterioration and erosion. Rotation of annual crops with improved pasture has been recommended to maintain or improve the soil's organic matter content (Deckers et al, 1998).

Set #7

Mineral Soils conditioned by a (semi-)Arid Climate

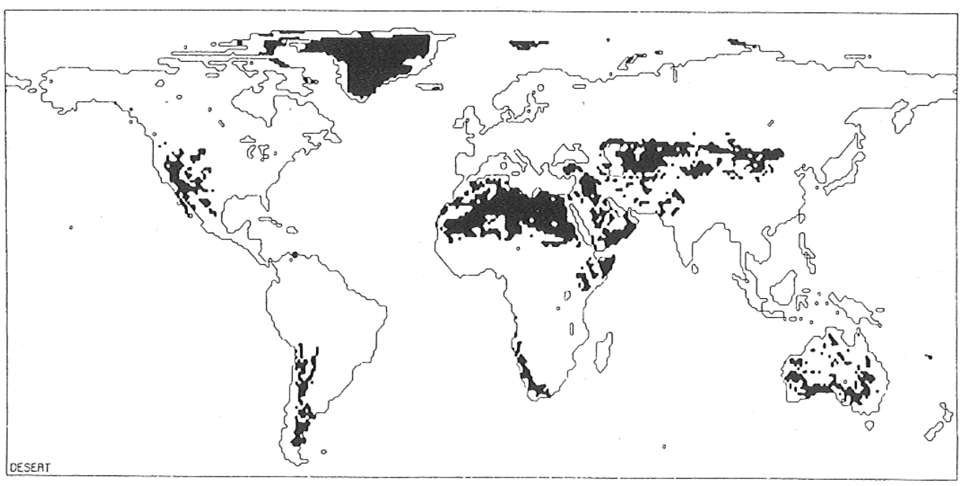
Major landforms in (semi-)arid regions

Arid and semi-arid regions are distinguished on the basis of their annual precipitation sums and include:

1. *Deserts* with an annual precipitation sum <50 mm/year and devoid of vegetation,
2. *Arid regions* with 50-250 mm/year precipitation and sparse vegetation, and
3. *Semi-arid regions* with a precipitation sum of 250 to 500 mm per annum and a steppe savannah/prairie/pampa vegetation.

Most deserts and (semi-)arid regions occur between 10° and 35° latitude (e.g. Sahara desert, Kalahari desert), in the interior parts of continents (e.g. Australia, Gobi desert) and in rain shadow areas in fold belts (e.g. Peru, Nepal). Large parts of the arctic tundra receive less then 250 mm precipitation per annum and qualify as 'arid regions' too. Figure 1 presents a sketch map of the desert areas of the world.

Figure 1
Desert areas of the world



Important geomorphic processes in the dry regions of the world differ from those in more humid environments:

1. *streams are intermittent or ephemeral* (and have very irregular discharges),
2. *mass–wasting processes and unconfined sheet floods* are prominent,
3. many *rivers do not debauch into the sea but end in inland depressions* without outlet,
4. *salt lakes* are a common landscape feature,
5. *aeolian processes* play an important role, particularly in areas below the 150 mm/year isohyet, and
6. *physical weathering processes are prominent* whereas hydrolysis of minerals is subdued.

Polar and subtropical fronts have shifted southwards in the (geologically) recent past and many regions that are arid today once had a more humid climate. Conversely, many of the present humid regions were much drier in glacial periods, especially between 20,000 and 13,000 BP when aeolian processes influenced land formation more than at present.

Mass wasting, fluvial processes and aeolian processes are the most important landform-shaping factors in arid and semi-arid regions. This chapter will solely discuss mass wasting and fluvial and lacustrine landforms in arid environments; sandy aeolian deposits were treated in an earlier chapter and loess deposits will be dealt with later when the major landforms of steppes and prairie regions will be discussed.

Mass-wasting processes

Mass-wasting processes are associated with strongly accidented terrain, e.g. where tectonic uplift has created mountains and in areas with steep fault scarps or incised valleys. Mass wasting often produces erosion landforms, such as residual hills or mountains that remain as isolated features in a low-relief plain. The residual elements consist normally of weathering-resistant rocks (e.g. Uluru sandstone, Australia) or are capped with a layer of resistant rock protecting the underlying softer rock from erosion (e.g. Utah, Great Monument National Park). Such a residual hill or table mountain is called an '*inselberg'* or *'mesa'*. Mountain foot slopes with a low slope angle and consisting of bedrock covered with a thin blanket of debris are termed '*pediments'*. Contrary to what it is often thought, pediments are erosional landforms because material is moved down the slope. Ultimately, severe erosion may create multiple, deeply incised valleys, in particular in areas with soft sedimentary rocks such as shale or marls, and create a '*badland'*.

The only depositional landform associated with mass wasting is the '*talus cone*' or '*rock debris cone*'. In barren deserts or mountains, temperature differences between day and night can be considerable and this frequently results in thermal disintegration of rocks. Salt crystals in the fissures may accelerate the process. Detached fragments of rocks and stones accumulate in debris cones at the foot of an inselberg or mountain.

Fluvial landforms in arid and semi-arid regions

Fluvial processes in arid regions produce typical landforms. These are different in high-relief and low-relief areas.

High-relief areas

Where a mountain front borders on a level plain, for instance at a major fault scarp or rift valley boundary, *'alluvial fans'* are likely to form. These form upon deposition of weathering products at the slope break. Debris flows and sheet floods during occasional heavy downpours are discharged from the hinterland via feeder canyons. Erosion products accumulate at the exit point (at the border between hinterland and plain) in a typical half-circular cone, the alluvial fan. The cone has a steep gradient and a pattern of unconfined channels that shift over the depositional body. As the water velocity of the protruding river becomes less, its sediment load can no longer be carried and much of it is deposited right at the entrance to the fan. This rapidly blocks the channel, which then sweeps left and right to evade the obstacle. The result is a low-angle sediment cone. The sediments tend to be coarser at the 'proximal' end of the fan (close to the fan head or apex) than at the 'distal' part (the fan toe, far into the plain.

Low-relief areas

Episodic heavy downpours in low-relief areas are often followed by overland flash floods and debris flows that follow existing depressions in the landscape. Such arid-region fluvial valleys are called *'wadis'*. Many wadis that are now found in desert regions formed during a more humid climatic episode between 13,000 and 8,000 years BP, at the transition from the Last Glacial to the Early Holocene. Wadis in desert regions carry water only after torrential rainstorms that normally occur once in a few years. At the onset of the rains, water can still infiltrate into the soil. As the downpours continue, the supply of water soon exceeds the infiltration capacity of the soil and excess water is discharged as surface run off: a '*flash flood'* is set in motion. Slaking and caking of the soil surface enhance surface run-off towards the wadis that become torrential braided streams with high sediment loads. These braided streams have only one channel, but multiple bars. After the downpour, the river will completely dry up again until the next event. Many wadis connect with dry, salty basins where individual floodplains merge into extensive *'playas'*. These are salty lakes with properties that will be outlined in the next paragraph.

Many inland depression areas in deserts are former lake areas in which open water was present during the early Holocene. Former river delta sequences and coastline features (e.g. coastal terraces) may still be visible.

Lacustrine landforms in arid and semi-arid regions

If a low-lying basin has no outlet, incoming water from (flash) floods evaporates inside the basin where its dissolved salts accumulate in the lowest parts. First, $CaCO_3$ and $MgCO_3$ precipitate as calcite, aragonite or dolomite. As the brine becomes further concentrated, gypsum ($CaSO_4.2H_2O$) segregates, and still later, when the lake is almost dry, halite (NaCl) and other highly soluble salts. Such salt lakes indicate that annual evapotranspiration is greater than the sum of incoming floodwater and precipitation. When such a *'playa'* dries out, the muddy lake floor shrinks and cracks. Accumulated salts crystallise and form crusts on top of the playa floor and in cracks in the surface soil. Much of the accumulated salts stem from (evaporitic marine sediments) outside the basin; many Mesozoic (Triassic, Jurassic) and Tertiary sediments are very rich in evaporites.

It depends on local hydrographic conditions whether a playa is wet around the year or dries out. A playa may stay (almost) permanently wet if it is part of a closed basin that is under the influence of groundwater. Some playas such as the Dead Sea are fed by perennial rivers and will not dry out either but their water is so salty that salts precipitate. Laminated evaporites of considerable thickness can form in this way, with lamination reflecting the periodicity of the seasons.

The largest evaporite basin formed in recent geological history is the Mediterranean basin. A closed, or almost closed, basin formed when mountain building blocked the Strait of Gibraltar some 6 million years ago. Before the Strait opened again, half a million years later, a layer of 1 kilometre of evaporites had accumulated on the basin floor.

Many lakes in present-day arid regions were freshwater lakes in the wet period between 12,000 and 8,000 BP. Terraces and/or shorelines from that period extend well above the present lake or lacustrine plain. The same lakes were completely dry in the arid Late Pleniglacial period (20,000-13,000 BP). Even a comparatively minor climate change can upset sedimentation regimes in arid lands.

Arid and semi-arid regions harbour a wide variety of soils that occur also in more humid environments (e.g. Leptosols, Regosols, Arenosols, Fluvisols). Typical dry-zone soils are soils whose formation was conditioned by aridity; accumulation and/or redistribution of anorganic compounds mark such soils.

High levels of soluble salts characterize Solonchaks; these soils are particularly common in closed depressions such as playas and inland basins. Solonetz are not marked by a high salt content, but by a high *proportion* of sodium ions in the soil solution and adsorbed at the cation exchange sites on clay and silt particles. Solonetz occur predominantly in temperate and subtropical, semi-arid region1s. Gypsisols shows signs of substantial accumulation of gypsum in the upper metre of soil; Calcisols are marked by accumulation of calcium carbonate. Gypsisols and Calcisols are found in a wide range of landforms, including pediments, lake bottoms, terraces and alluvial fans. Durisols with a 'duric' or 'petroduric' horizon that is hardened by silica (SiO_2) cementation, are not exclusive to arid regions but most Durisols occur in drylands, e.g. alongside Calcisols or Gypsisols.

SOLONCHAKS (SC)

The Reference Soil Group of the Solonchaks includes soils that have a high concentration of 'soluble salts' at some time in the year. Solonchaks are largely confined to the arid and semi-arid climatic zones and to coastal regions in all climates. Common international names are 'saline soils' and 'salt-affected soils'.

Definition of Solonchaks[#]

Soils,
1. having a *salic*[@] horizon starting within 50 cm from the soil surface; and
2. lacking diagnostic horizons other than a *histic*[@], *mollic*[@], *ochric*[@], *takyric*[@], *yermic*[@], *calcic*[@], *cambic*[@], *duric*[@], *gypsic*[@] or *vertic*[@] horizon.

Common soil units:
Histic*, Gelic*, Vertic*, Gleyic*, Mollic*, Gypsic*, Duric*, Calcic*, Petrosalic*, Hypersalic*, Stagnic*, Takyric*, Yermic*, Aridic*, Hyperochric*, Aceric*, Chloridic*, Sulphatic*, Carbonatic*, Sodic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Solonchaks

Connotation: saline soils; from R. *sol*, salt, and R. *chak*, salty area.

Parent material: virtually any unconsolidated soil material.

Environment: arid and semi-arid regions, notably in seasonally or permanently waterlogged areas with grasses and/or halophytic herbs, and in poorly managed irrigation areas. Solonchaks in coastal areas occur in all climates.

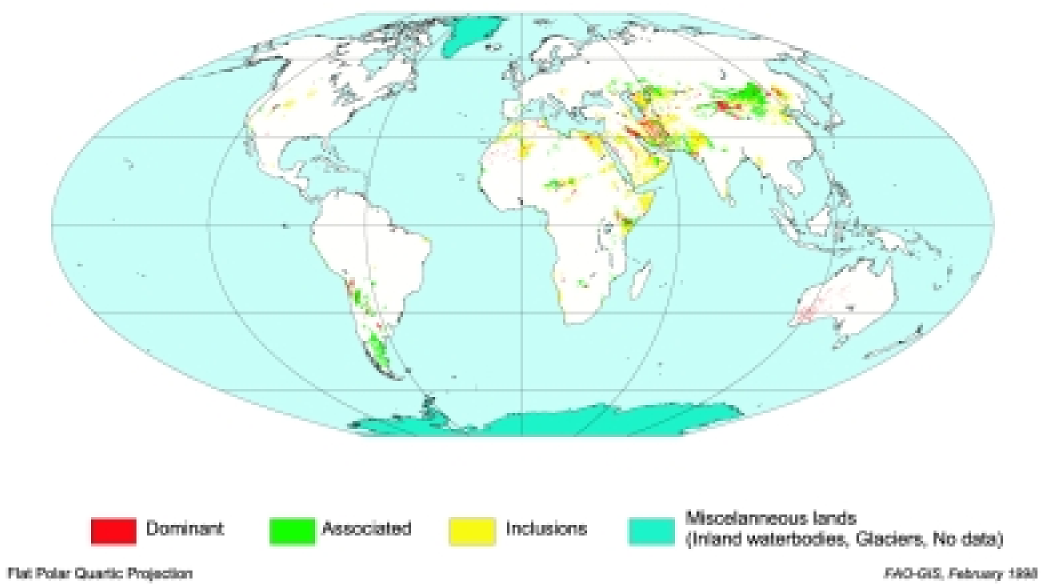
Profile development: mostly AC or ABC profiles, often with *gleyic* properties at some depth. In low-lying areas with a shallow water table, salt accumulation is strongest at the surface of the soil ('*external Solonchaks'*). Solonchaks with a deep water table have the greatest accumulation of salts at some depth below the surface (*internal Solonchaks'*).

Use: Solonchaks have limited potential for cultivation of salt-tolerant crops. Many are used for low volume grazing or are not used for agriculture at all.

Regional distribution of Solonchaks

The total extent of Solonchaks in the world is estimated to be between 260 million (Dudal, 1990) and 340 million hectares (Szabolcs, 1989), depending on the level of salinity that is taken as diagnostic. Solonchaks are most extensive in the Northern Hemisphere, notably in arid and semi-arid parts of northern Africa, the Middle East, the former USSR and central Asia; they are also widespread in Australia and the Americas. Figure 1 shows the major occurrences of Solonchaks in the world.

Figure 1
Solonchaks world-wide



Associations with other Reference Soil Groups

Solonchaks have in common that they have a 'high' salt content in some part or all of the control section. *Note that* also other Reference Soil Groups than Solochaks may have a *salic* horizon. Such soil groups have other properties that are considered more characteristic than the salic horizon and key out before the Solonchaks, e.g. Histosols, Vertisols and Fluvisols; their salic soil units are intergrades to Solonchaks.

Genesis of Solonchaks

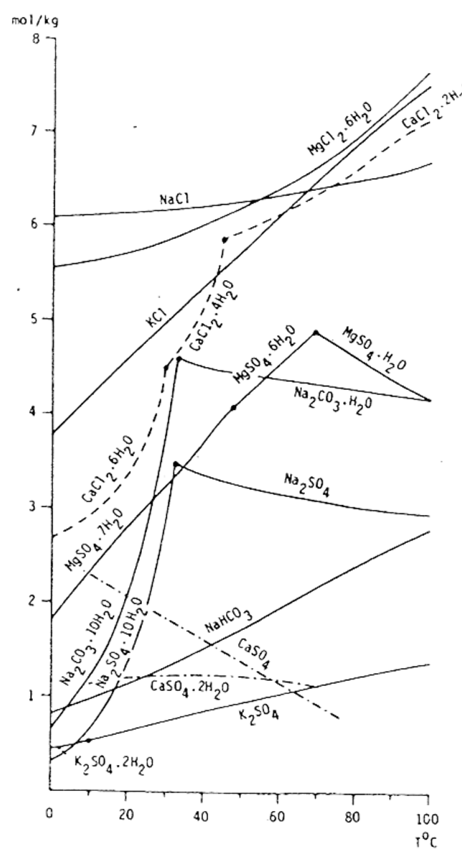
The most extensive occurrences of Solonchaks are in inland areas where evapotranspiration is considerably greater than precipitation, at least during a greater part of the year. Salts dissolved in the soil moisture remain behind after evaporation/transpiration of the water and accumulate at the surface of the soil ('*external Solonchaks*') or at some depth ('*internal Solonchaks*'). The Reference Soil Group of the Solonchaks is heterogeneous by nature. Solonchaks may differ in

- the *content and depth of salts* in the soil,
- the *composition* of accumulated salts,
- the *mineralogy* of salt efflorescences.

Content and depth of accumulated salt(s)

Figure 2 reveals that the solubility of most salts is temperature-dependent. The solubility product is greater in the warm dry season when there is a net upward water flux from the groundwater table to the surface soil, than in the cooler wet season when salts are leached from the surface soil by surplus rainfall. This *hysteresis* between (rapid) influx of salts in the soil and (slow) discharge is conducive to net accumulation of salts (and development of a *salic* soil horizon) in seasonally dry regions. External Solonchaks form in depression areas with strong capillary rise of saline groundwater and in poorly managed irrigation areas where salts imported with irrigation water are not properly discharged through a drainage system. Internal Solonchaks develop where the water table is deeper and capillary rise cannot fully replenish evaporation losses in the dry season. Internal Solonchaks may also form through leaching of salts from the surface to deeper layers, e.g. by surplus irrigation or by natural flushing of the soil during wet spells. The *'critical depth'* of the groundwater, i.e. the depth below which there is little danger that harmful (quantities of) salts will accumulate in the rooted surface soil, depends on soil physical characteristics but also on the climate. The USDA Soil Survey Staff considers a depth of 6 feet critical "especially if the surface is barren and capillary rise is moderate to high".

Figure 2
Solubility of common salts in Solonchaks, expressed in mole anhydrous salt per kg H_2O, as a function of the soil temperature (Braitsch, 1962)



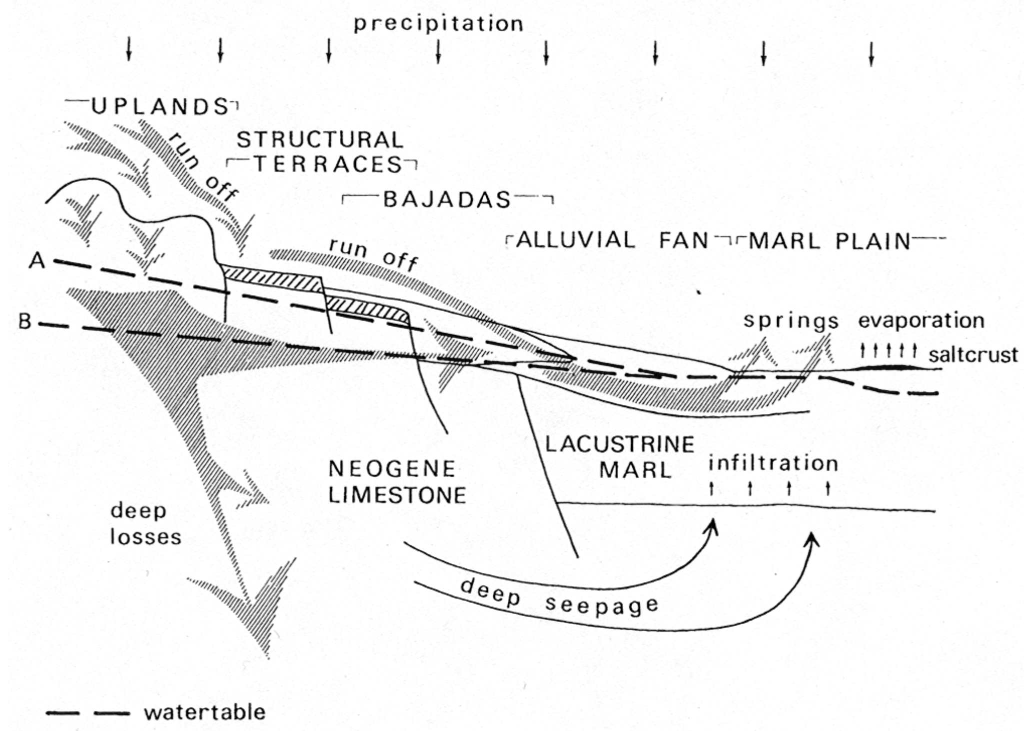
Composition of accumulated salts

Salts in areas with strongly saline soils are more often than not imported with river water from far-away catchment areas or with seepage water or surface run off from nearby uplands. Accumulated salts can often be traced to deeper geological strata of marine origin (chlorides) or to volcanic deposits (sulphates). Figure 3 presents a diagram of a common situation with Solonchaks in bottomland that receives water (and salts) from adjacent uplands. Much soil salinity is man-induced through irrigation in combination with inadequate drainage.

French soil scientists differentiate saline soils by the dominant cations in the soil, in particular the ratio of bivalent and monovalent cations (Duchaufour, 1988; Loyer *et al.*, 1989). For practical reasons they distinguish between:

- *calcium-dominated* saline soils, characterized by a dominance of calcium and magnesium over sodium and potassium. The ratio of $(Ca^{++}+Mg^{++})/(Na^{+}+K^{+})$ is between 1 and 4 and the Ca^{++}/Mg^{++}-ratio is 1 or greater. It is widely believed that the structure of calcium dominated soils remains stable even when the salts are flushed out of the soil.

Figure 3
Schematic representation of import and redistribution of salts in the Great Konya Basin, Turkey. Watertable A in spring (May); B in autumn (September). Source: Driessen & v.d. Linden, 1970



- *sodium-dominated* saline soils, in which the ratio of $(Ca^{++}+Mg^{++})/(Na^{+}+K^{+})$ in the soil solution is less than 1. The structure of these soils tends to degrade when the salts are flushed out of the soil.
- *magnesium-dominated* saline soils, in which the ratio of $(Ca^{++}+Mg^{++})/(Na^{+}+K^{+})$ in the soil solution is greater than 1, the Ca^{++}/Mg^{++}-ratio equals 1 or less, and the Na^{+}/Mg^{++} ratio is less than 1. Desalinization of such soils provokes hydrolysis of adsorbed Mg^{++} ions, which is generally associated with degradation of the soil structure.

Russian soil scientists characterize 'salt provinces' on the basis of anion ratios. See Table 1.

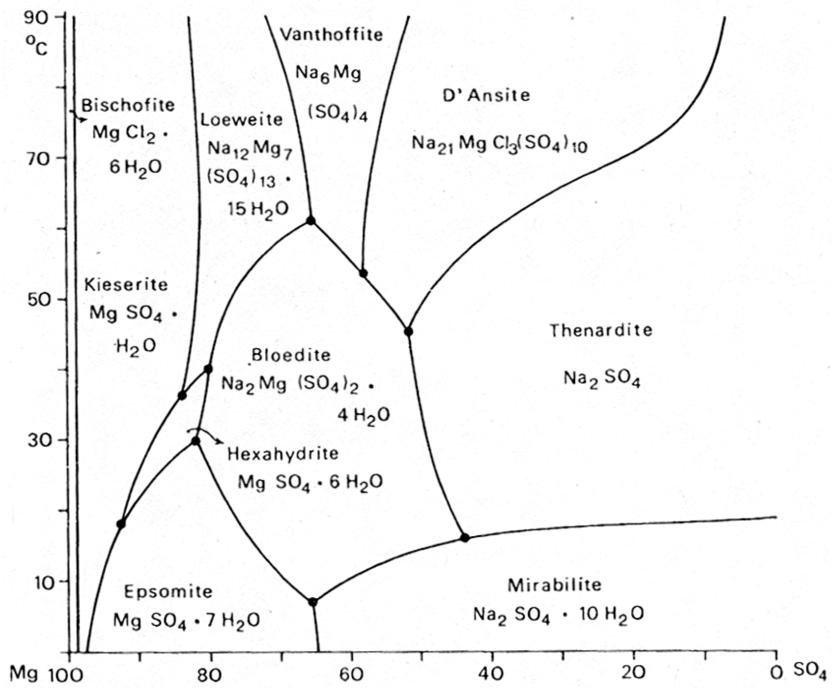
TABLE 1
Classification of saline soils based on anion ratios (Plyusnin, 1964)

		Pljusnin	Rosanov	Sadovnikov
Sulphate soils	Cl^{-}/SO_4^{--}	<0.5	<0.2	<0.2
Chloride-sulphate s.	Cl^{-}/SO_4^{--}	0.5-1.0	0.2-1.0	0.2-1.0
Sulphate-chloride s.	Cl^{-}/SO_4^{--}	1.0-5.0	1.0-2.0	1.0-5.0
Chloride soils	Cl^{-}/SO_4^{--}	>5.0	>2.0	>5.0
Soda soils	CO_3^{--}/SO_4^{--}			<0.05
Sulphate-soda soils	CO_3^{--}/SO_4^{--}			0.05-0.16
Soda-sulphate soils	CO_3^{--}/SO_4^{--}			>0.16

Mineralogy of salt efflorescences

The morphology of saline soils is to some extent conditioned by the *mineralogy of salts* in the soil. Figure 4 presents the stability diagram of minerals in an NaCl-saturated NaCl-Na_2SO_4-$MgCl_2$-H_2O system. The diagram demonstrates that diurnal temperature fluctuations may already induce mineralogical transformations.

Figure 4
Stability diagram of minerals in an NaCl-saturated NaCl-Na_2SO_4-$MgCl_2$-H_2O system.
Source: Braitsch, 1962



An example of a specific type of Solonchak which forms under the influence of *diurnal* (temperature-induced) fluctuations in the morphology of salts is the *'puffed Solonchak'*, an externally saline soil in which the greater part of all salt consists of sodium sulphate. At night, when the temperature at the soil surface is low and air humidity is high, crystalline sodium sulphate is present in the surface soil as -shaped *mirabilite* ($Na_2SO_4.10H_2O$). See Figure 4.

The needle-shaped mirabilite crystals push fine soil aggregates apart when they are formed. When the temperature rises again during the day, mirabilite is re-converted to water-free *thenardite* (Na_2SO_4) crystals that have the appearance of fine flour. Repeated mirabilite-thenardite transformations produce the soft and fluffy surface soil that characterizes a puffed Solonchak.

Another example of *diurnally* changing external Solonchaks concerns soils with a dominance of *hygroscopic* salts such as $CaCl_2$ or $MgCl_2$, and to a lesser extent also NaCl. The resulting '*sabakh*' soils ('sabakh' is arabic for morning) are dark-coloured and slippery in the morning as a result of moisture absorption during the night. The soils lose their dark colour again in the course of the day when the temperature rises and air humidity drops to a low value.

An example of an *annual* cycle in which the morphology of salt minerals plays a role is the formation of *'slick spots'*, isolated patches of very saline and soft mud in a field. Slick spots appear early in the dry season in shallow depressions (often hardly recognisable with the naked eye). The depressions are covered with a salt crust, e.g. a glass-like *halite* (NaCl) crust, that is so effective in sealing the underlying saline mud from the air that the soil remains wet throughout the dry season. Pores or cracks that can provide passage to rain or leaching water will not form. The crust may dissolve in a subsequent wet season but the unripe, impermeable mud remains saline and restores its protective crust as soon as the wet season is over. The untrafficable and very saline slick spots cannot be reclaimed with conventional (leaching) techniques.

Characteristics of Solonchaks

Morphological characteristics

The horizon differentiation of Solonchaks is normally determined by other factors than their high salt content. Many saline soils in waterlogged backswamps are Gleyic Solonchaks; without their salic horizon they would have been Gleysols. Likewise, Mollic Solonchaks may have the appearance of a Chernozem, Kastanozem or Phaeozem, and Calcic and Gypsic Solonchaks are basically strongly saline Calcisols and Gypsisols. Saline Histosols, Vertisols and Fluvisols occur as well; they are not classified as Solonchaks because Histosols, Vertisols and Fluvisols key out before Solonchaks.

Solonchaks have a stable soil structure accounted for by the high salt content of the soil but a typical structural expression of Solonchaks does not exist. Especially in heavy clays, very saline surface layers may exist without any clear efflorescence of salts. Examination with a lens reveals tiny crystals on the faces of crumb or granular structure elements. In extreme cases, very saline pseudo-sand may form that accumulates to clay dunes when exposed to strong winds. The other extreme occurs also: clayey 'external Solonchaks' may lose their surface structure when exposed to an occasional rain shower. The peptised surface layer will subsequently dry out to a hard crust. When the crust is still soft, it may be pushed upwards by gases escaping from the underlying mud; prints of gas bubbles remain visible when the crust is detached from the underlying wet soil. Recall that the surface layer of *'sabakh'* soils is a muddy mixture of salt and soil particles during early morning hours. The fluffy top layer of puffed Solonchaks is a morphological feature that is exclusive to Solonchaks with a high content of sodium sulphate. The most common type of salt crust, however, is a loose cover of salt crystals.

The morphology of internal Solonchaks differs little from that of comparable non-saline soils. Solonchaks have, perhaps, a somewhat stronger subsoil structure with, in very saline soils, tiny salt crystals on the faces of structure elements.

With a *salic* horizon as the only common characteristic, there is considerable diversity among Solonchaks and a detailed account of their hydrological, physical, chemical and biological properties is not well possible. A few general trends:

Hydrological characteristics

Internal Solonchaks are largely confined to areas that lie well above the drainage base. When leached, they may actually furnish (part of) the salts that accumulate in contiguous bottomland with external Solonchaks. Extremely saline soils with thick surface crusts occur in depressions that collect water from surrounding (higher) land in the winter but dry out in the warm season. Such soils are also referred to as *'flooded' Solonchaks*.

Figure 5
Schematic cross-section of the Great Konya Basin, Turkey. *Note that* topography and hydrology influence salinity patterns. All concentrations are expressed in mM/liter 'saturation extract' or groundwater

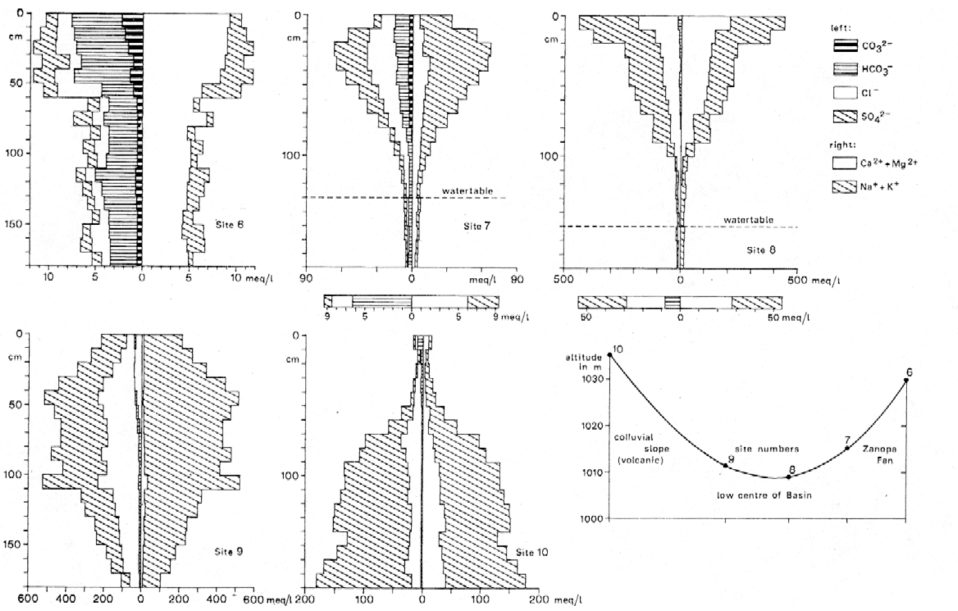


Figure 5 presents a schematic cross-section through an inland basin with severe soil salinity:

- Where the water table is at shallow depth, strongly externally saline Gleyic Solonchaks occur (site 8).
- Slightly above the base level (site 9), the soils are still strongly saline but the highest concentration of salts is at some depth in the soil. This suggests a combination of upward salt transport from the groundwater through capillary rise and downward leaching of salt from the surface soil to the zone with the highest salt concentration.
- In still higher areas with a deep water table (site 10), non-saline Calcisols and internally saline Calcic Solonchaks occur.
- Sites 6 and 7 are located on an alluvial fan that drains freely to the low centre of the basin. Soils on the upper part of the fan are invariably non-saline; there is beginning salinization in the lower tract where the groundwater table is at shallow depth. (Note the different scales of the x-axis.)

Physical characteristics

Solonchaks that dry out during part of the year tend to have strong structure elements. When the salt content is lowered by winter rains or irrigation water, soil structure may degrade, particularly if the salts contain sodium and/or magnesium compounds. Strong peptisation of clays at the onset of (winter) rains may make the surface soil virtually impermeable to water.

Chemical characteristics

The salt content of Solonchaks is normally judged by considering the *ECe-value*, i.e. the 'Electric Conductivity of a saturation extract'. The ECe value is obtained by puddling an aliquot of water-saturated soil and subsequently measuring the electrical resistance between two electrodes submerged in (some of) the saturation extract. The reciprocal value of the resistance measured is the ECe, expressed in mho/cm (in older literature) or dS/m (S stands for 'Siemens'). As a rule of thumb (*sic!*), a soil extract or water sample contains some 0.6 grams of dissolved salts per liter for every dS/m measured.

A *salic* soil horizon has an ECe value in excess of 15 dS/m at 25 °C at some time of the year, or more than 8 dS/m if the soil-pH (H_2O,1:1) is greater than 8.5 (alkaline carbonate soils) or less than 3.5 (acid sulphate soils). Extracts of saturated soil pastes are used in base laboratory work; for quick orientation, the electric conductivity is often determined on 1:1 or 1:5 soil extracts (EC_1 or EC_5). Values obtained with different methods cannot always be compared, *inter alia* because a 'suspension effect' (different at different dilution ratios) influences the outcome of the conductivity measurement.

Biological characteristics

Faunal activity is depressed in most Solonchaks and ceases entirely in soils with 3 percent salt or more. In severely salt-affected lands, the vegetation is sparse and limited to halophytic shrubs, herbs and grasses that tolerate severe physiological drought (and can cope with periods of excessive wetness in areas with seasonally flooded Solonchaks).

Land use and management of Solonchaks

Excessive accumulation of salts in soil affects plant growth in two ways:

1. The salts aggravate drought stress because dissolved electrolytes create an '*osmotic potential'* that affects water uptake by plants. Before any water can be taken up from the soil, plants must compensate the combined forces of the soil's '*matrix potential'*, i.e. the force with which the soil matrix retains water, and the osmotic potential. As a rule of thumb *(sic!)* the osmotic potential of a soil solution (in hPa) amounts to some 650 * EC (in dS/m). The total potential that can be compensated by plants (known as the '*critical leaf water head*') varies strongly between plant species. Plant species that stem from the humid tropics have a comparatively low 'critical leaf water head'. Green peppers, for instance, can compensate a total soil moisture potential (matrix plus osmotic forces) of only some 3,500 hPa whereas cotton, a crop that evolved in arid and semi-arid climates, survives some 25,000 hPa! Table 2 presents a widely used key for grading of salt affected soils with attention for the harmful effects of soil salinity on crop performance.

TABLE 2
Indicative soil salinity classes and implications for crop performance

ECe at 25 °C (dS/m)	Salt Concentration (cmol/l)	(percent)	Effect on crops
<2.0	<2		mostly negligible
2.0-4.0	2-4	<0.15	some damage to sensitive crops
4.0-8.0	4-8	0.15-0.35	serious damage to most crops
8.0-15.0	8-15	0.35-0.65	only tolerant crops succeed
>15	>15	>0.65	few crops survive

Note that Table 2 gives merely an indication: the damage done to a particular crop depends as much on the moisture content of the rooted soil as on the salt content of the saturated soil (extract). Farmers on Solonchaks know this and adapt their cultivation methods. An example:

plants on furrow-irrigated fields are not planted on the crest of the ridges but at half height. This ensures that the roots benefit from the irrigation water while salt accumulation is strongest near the top of the ridge, away from the root systems.

2. Dissolved salts upset the balance of ions in the soil solution; nutrients are proportionally less available. Antagonistic effects are known to exist, for example, between sodium and potassium, between sodium and calcium and between magnesium and potassium. In higher concentrations, the salts may be directly toxic to plants. Very harmful in this respect are sodium ions and chloride ions (disturb N-metabolism).

Strongly salt-affected soils have little agricultural value: they are used for extensive grazing of sheep, goats, camels and cattle or lie idle. Only after the salts have been flushed from the soil (which then ceases to be a Solonchak) may good yields be hoped for. Application of irrigation water must not only satisfy the needs of the crop but excess water must be applied above the irrigation requirement to maintain a downward water flow in the soil and flush excess salts from the root zone. Irrigation of crops in arid and semi-arid regions must be accompanied by drainage whereby drainage facilities should be designed to keep the groundwater table below the critical depth.

SOLONETZ (SN)

The Reference Soil Group of the Solonetz accommodates soils with a dense, strongly structured, clay illuviation horizon that has a high proportion of adsorbed sodium and/or magnesium ions. The name 'Solonetz' (from R. *sol*, salt, and *etz*, strongly expressed) has become somewhat confusing now that most saline soils, with or without a high proportion of adsorbed sodium ions, key out as Solonchaks in the WRB key. Solonetz that contain free soda (Na_2CO_3) are strongly alkaline (field pH > 8.5). Internationally, Solonetz are referred to as 'alkali soils' and 'sodic soils', 'Sols sodiques à horizon B et Solonetz solodisés' (France), Natrustalfs, Natrustolls, Natrixeralfs, Natrargids or Nadurargids (USA) and as Solonetz (USSR, Canada, FAO).

Definition of Solonetz[#]

Soils having a *natric*[@] horizon within 100 cm from the soil surface.

Common soil units:
Vertic*, Salic*, Gleyic*, Mollic*, Alcalic*, Gypsic*, Duric*, Calcic*, Stagnic*, Humic*, Albic*, Takyric*, Yermic*, Aridic*, Magnesic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups.
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Solonetz

Connotation: Soils with a high content of exchangeable sodium and/or magnesium ions; from R. *sol*, salt, and *etz*, strongly expressed.

Parent material: unconsolidated materials, mostly fine-textured sediments.

Environment: Solonetz are normally associated with flat lands in a climate with hot, dry summers, or with (former) coastal deposits that contain a high proportion of sodium ions. Major concentrations of Solonetz are in flat or gently sloping grasslands with loess/loam or clay in semi-arid, temperate and subtropical regions.

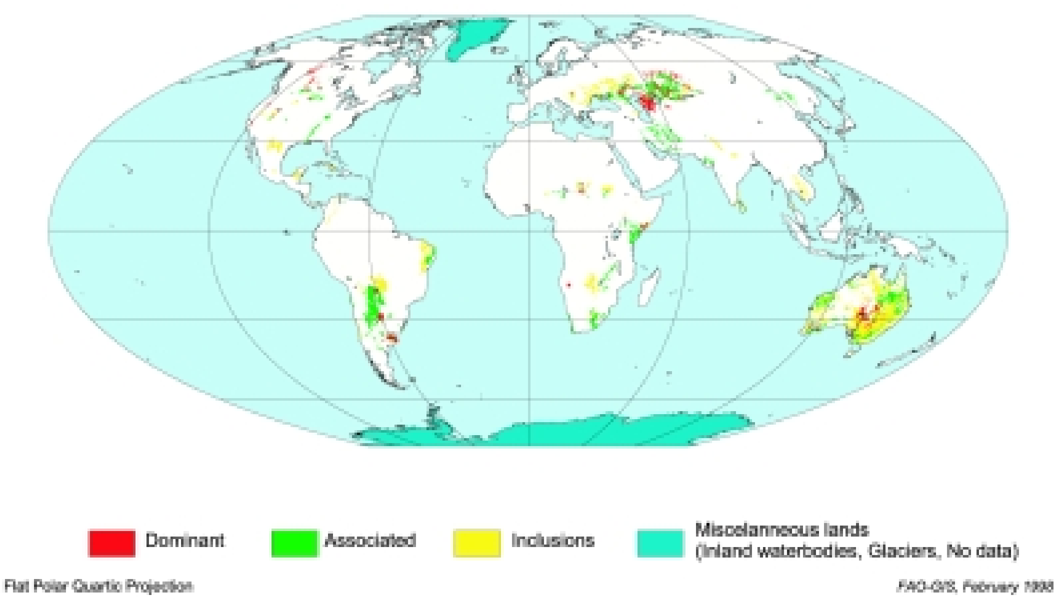
Profile development: ABtnC and AEBtnC profiles with a black or brown surface soil over a *natric* horizon that starts at less than 100 cm from the soil surface. Well-developed Solonetz can have a (beginning) *albic* eluviation horizon directly over a natric horizon with strong round-topped columnar structure elements. A *calcic* or *gypsic* horizon may be present below the natric horizon. Many Solonetz have a field-pH above 8.5 indicative of the presence of free sodium carbonate.

Use: high levels of exchangeable sodium ions affect arable cropping, either directly (Na-toxicity) or indirectly, e.g. because of structure deterioration when soil material with a high proportion of adsorbed sodium and/or magnesium ions is wetted. Many Solonetz in temperate regions have a humus-rich surface soil and can (still) be used for arable farming or grazing; Solonetz in semi-arid regions are mostly used as range land or lie idle.

Regional distribution of Solonetz

Solonetz occur predominantly in areas with a steppe climate (dry summers and an annual precipitation sum of not more than 400 to 500 mm), in particular in flat lands with impeded vertical and lateral drainage. Smaller occurrences are found on inherently saline parent materials (e.g. marine clays or saline alluvial deposits). Worldwide, Solonetz cover some 135 million hectares. Major Solonetz areas are found in the Ukraine, Russia, Kazakhstan, Hungary, Bulgaria, Rumania, China, USA, Canada, South Africa and Australia.

Figure 1
Solonetz world-wide



In the past, Solonetz were frequently lumped into one broad soil group with Solonchaks: the “salt-affected soils”. However, Solonetz need not be saline and Solonetz and Solonchaks often have quite different morphological and physico-chemical properties, and consequently also different management requirements. At present, Solonetz and Solonchaks are separated at a high taxonomic level in most national soil classification systems.

Associations with other Reference Soil Groups

Solonetz are frequently associated with:

- *Chernozems* and *Kastanozems*, mainly in landscapes with loess-loam that have some micro-relief and poor surface drainage (e.g. in the Hungarian ‘puszta’, the flat lands of the Volga delta in Russia, and the central part of the Canadian shield);
- *Solonchaks* in arid and semi-arid regions, in particular in the central and peripheral parts of large depressions;

- *Histosols*, notably in bottom lands in aeolian (loess-covered), lacustrine and riverine landscapes within the steppe zone;
- *Vertisols* in plains that are affected by saline groundwater, e.g. in the Gezira region of the Sudan.

Micro-relief, periodical water logging, and the spatial variability of soil and groundwater salinity determine lateral soil sequences in regions with Solonetz.

Genesis of Solonetz

The essential characteristic of Solonetz is their *natric* subsurface horizon, which shows signs of clay translocation and has an 'Exchangeable Sodium Percentage' (ESP) of 15 or greater in the upper 40 cm of the horizon. The ESP, defined as *'100 * exchangeable Na / CEC'*, reflects the chemical composition of the soil solution in equilibrium with the solid soil material *under conditions as prevailed during the CEC determination*. The WRB definition of a natric horizon waives the requirement of ESP > 15 in the upper 40 cm of the natric horizon. It suffices that soil at that depth contains "more exchangeable Mg plus Na than Ca plus exchange acidity (at pH 8.2)" *if* ESP > 15 in some sub-horizon within 200 cm of the surface.

The sodium that is responsible for the high ESP-value may originate from areas with a marine history. Many Solonetz in inland areas contain sodium sulphates ($Na_2SO_4.xH_2O$) or $Na_2CO_3.xH_2O$ ('soda') as the dominant sodium compound. It is widely thought that soda can form in two ways:

(1) by *evaporation of water* that contains excess of bicarbonate ions over (Ca^{2+} + Mg^{2+})
(2) biologically, by *reduction of sodium sulphate*.

Excess bicarbonate is in practice always sodium bicarbonate, which is eventually transformed to Na_2CO_3. The biological formation of soda from sodium sulphate is said to follow the sequence Na_2SO_4 à Na_2S à Na_2CO_3 + H_2S, whereby hydrogen sulfide gas leaves the system. This reaction requires (periods of) anaerobic conditions and the presence of organic matter in addition to sodium sulphate.

The formation of a natric horizon is not (yet) properly researched but seems furthered by annual fluctuations in temperature and soil moisture content. The solubility of common sodium and magnesium compounds in soil such as $Na_2SO_4.10H_2O$, $Na_2CO_3.10H_2O$ and $MgSO_4.7H_2O$, increases sharply over the temperature range from 0 to 30 ^oC (see under Solonchaks; Figure 2). Rapid accumulation of these compounds in the surface soil during dry and hot summer seasons is followed by much slower leaching during the wet but cold winter season. Hysteresis between rapid accumulation and slow discharge of sodium and magnesium compounds in the (sub)surface soil is certainly to be expected in regions with a continental climate where summers are dry and warm and winter precipitation is largely snow that melts in early spring (leaching water temperature close to freezing point). The fact that major Solonetz areas are found in the dry interior parts of North America, Eurasia and Australia seems to confirm this hypothesis.

The presence of 'free' soda in soil is associated with a field-pH > 8.5. Under such conditions, organic matter tends to dissolve and move through the soil body with moving soil moisture. The remaining mineral soil material is bleached and in the extreme case a clear eluvial horizon may form directly over the dense natric subsurface horizon. Black spots of accumulated organic matter can be seen in many Solonetz, at some depth in the natric horizon. The dense natric (clay) illuviation horizon poses an obstacle to water percolating downward at the beginning of a wet season. Rain water or snowmelt contains little sodium, if any. This causes a sudden drop in the ionic strength and sodium concentration of the soil moisture at the wetting front. As a consequence, the water films *('double layers')* around individual clay plates become thicker, which weakens the bonds between negatively charged sides of clay plates and positively charged 'ends' of other plates. Soil aggregation is thus weakened and the soil material disperses. This process is held accountable for the rounded tops of (columnar) structure elements in mature natric horizons. Where the surface soil is subsequently lost because of erosion, the exposed natric horizon shows a characteristic 'cobblestone' pattern. Black flakes of translocated organic matter can often be seen on top of the exposed natric horizon alongside whitish, bleached mineral particles. It has been reported that in extreme cases silica and alumina will even dissolve from silicate clays at the upper boundary of the natric horizon.

Note that not all Solonetz contain soda and have a high field-pH! Solonetz can also form through progressive leaching of salt-affected soil. Even soils that were initially rich in calcium may eventually develop a natric horizon. Prolonged leaching and exchange of adsorbed Na^+ by H^+ will ultimately produce a bleached eluvial horizon with a low pH. Such strongly degraded soils are known as *'Solods'*.

Characteristics of Solonetz

Morphological characteristics

'Typical' Solonetz feature a thin, loose litter layer resting on black humified material about 2-3 cm thick. The surface horizon is brown, granular and shallow but can also be more than 25 cm thick; it is easily eroded away. If still present, it normally overlies a brown to black, coarse columnar or prismatic, natric subsurface horizon. Structure elements in the natric horizon may be covered by thick, dark cutans of clay and/or translocated organic matter, especially if the soil reaction is strongly alkaline. The rounded tops of columnar structure elements may be covered with bleached, powdery fine sand or silt. In strongly degrading Solonetz, a bleached '*albic* horizon' may even be present between the surface horizon and the natric horizon. The natric horizon grades with depth into massive subsoil.

Hydrological characteristics

Clayey Solonetz are nearly always slowly permeable to water. Rapid slaking of surface soil during rain showers (or surface inundation) and subsequent ponding of water on top of dry (*sic!*) soil is a common problem. Shallow drainage gullies are common even in (nearly) flat depression areas, which demonstrates how rapid dispersion of surface soil material is conducive to water erosion of Solonetz.

Physical characteristics

Most Solonetz are very hard in the dry season and sticky when wet. Clayey Solonetz tend to become lumpy at the surface when ploughed, particularly where the shallow surface horizon was lost and the top of the natric horizon became exposed. The dense natric horizon hinders downward percolation of water and root penetration. There are strong indications that a high percentage of exchangeable magnesium affects the soil structure in a similar manner as a high ESP.

Chemical characteristics

The strong sodium saturation of Solonetz is harmful to plants in several ways.

- Too much sodium in the soil is *directly toxic* to Na^+-sensitive plants and disturbs uptake of essential plant nutrients.
- Excess sodium affects plant growth *indirectly* because the dense natric horizon obstructs downward percolation of water and the growth of roots.

The impression exists that sensitive crops (e.g. beans) develop true sodium toxicity symptoms already at low ESP-values whereas tolerant crops such as cotton become stunted at much higher ESP, mainly because of sodium-induced adverse physical soil conditions.

MANAGEMENT AND USE OF SOLONETZ

The suitability of 'virgin' Solonetz for agricultural uses is almost entirely dictated by the depth and properties of the surface soil. A 'deep' (say >25 cm) humus-rich surface soil is needed for successful arable crop production. Unfortunately, most Solonetz have only a much shallower surface horizon, or have lost the surface horizon altogether.

Solonetz amelioration has two basic elements:

- *improvement of the porosity* of the (sub)surface soil, and
- lowering of the ESP.

Most reclamation attempts start with incorporation of gypsum or, exceptionally, calcium chloride in the soil. Where lime or gypsum occur at shallow depth in the soil body, deep ploughing (mixing the carbonate or gypsum containing subsoil with the surface soil) may make expensive amendments superfluous. Traditional reclamation strategies start with the planting of a sodium-resistant crop, e.g. Rhodes grass, to gradually improve the permeability of the soil. Once a functioning pore system is in place, sodium ions are carefully leached from the soil with 'good quality' (calcium-rich) water.

An extreme reclamation method, which was developed in Armenia and successfully applied to Calcic Solonetz soils in the Arax river valley, uses diluted sulphuric acid (a waste product of the metallurgical industry) to dissolve $CaCO_3$ contained in the soil. This adds calcium ions to the soil solution, which repel sodium ions from the soil's exchange complex. The practice improves soil aggregation and soil permeability. The resulting sodium sulphate (in the soil solution) is subsequently flushed out of the soil.

By and large, Solonetz are problem soils when used for arable agriculture. The prospects for crop production on Solonetz are largely dictated by the thickness of the humus-rich surface layer. Deep ploughing can improve Solonetz in areas where lime or gypsum is present at shallow depth in the soil. This strategy and the use of ameliorants such as gypsum were found to be the most effective on Solonetz under irrigation. Ameliorated Solonetz can produce a fair crop food grain or forage. The majority of the world's Solonetz was never reclaimed and is used for extensive grazing or lies idle.

A word of caution

Soil analytical laboratories determine the Exchangeable Sodium Percentage (ESP) of soil material in a number of steps. First, 'adsorbed bases' are determined by bringing an aliquot of the soil material in contact with a strong electrolyte solution such as 1 M NH_4-acetate. After 'equilibrium' is established, repelled 'bases' (Na^+ and Mg^{2+}-ions and others) are determined in the acetate solution. Next, the exchange capacity of the soil material is determined by exposing the same aliquot of soil to another electrolyte solution that is buffered to a constant pH-value, e.g. pH 7.0 or pH 8.2. The ESP-value is calculated by multiplying the quantity of repelled Na^+ (first electrolyte solution) by 100 and dividing the result by the quantity of the repelled replacement cation (determined in second electrolyte solution).

The cation exchange properties of many soil materials are in part pH-dependent. This has consequences: the actual ESP-value *under field conditions* is overestimated if the field-pH exceeds the value of the buffered (second) electrolyte solution and is underestimated if the field-pH is lower. It follows that (widely used) generic tables that suggest orders of crop yield depression as a function of measured ESP-values overestimate damage if the field-pH exceeds the pH of the buffered electrolyte solution and underestimate damage is the field-pH is lower. This explains why cotton can be produced in the Gezira region of Sudan (field-pH > 8.5 and a *measured* ESP-value of 35%) even though tables published in the United States indicate a maximum tolerable ESP-level of only 16% (at a field-pH close to 7.0). Generic tables on the damage inflicted by high sodium levels are to be used with great caution!

GYPSISOLS (GY)

Gypsisols are soils with substantial secondary accumulation of gypsum ($CaSO_4.2H_2O$). They are found in the driest parts of the arid climate zone, which explains why leading soil classification systems labeled them 'Desert soils' (USSR), Aridisols (USDA Soil Taxonomy), Yermosols or Xerosols (FAO, 1974).

Definition of Gypsisols[#]

Soils having
1. a *gypsic*[@] or *petrogypsic*[@] horizon within 100 cm from the surface; and
2. no diagnostic horizons other than an *ochric*[@] horizon, a *cambic*[@] horizon, an *argic*[@] horizon permeated with gypsum or calcium carbonate, a *vertic*[@] horizon, or a *calcic*[@] or *petrocalcic*[@] horizon underlying the *gypsic*[@] or *petrogypsic*[@] horizon.

Common soil units:
Petric*, Hypergypsic*, Leptic*, Vertic*, Endosalic*, Duric*, Calcic*, Luvic*, Takyric*, Yermic*, Aridic*, Hyperochric*, Skeletic*, Sodic*, Arzic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Gypsisols

Connotation: soils with substantial secondary accumulation of calcium sulphate; from L. *gypsum*, gypsum.

Parent material: mostly unconsolidated alluvial, colluvial or aeolian deposits of base-rich weathering material.

Environment: predominantly level to hilly land and depression areas (e.g. former inland lakes) in arid regions. The natural vegetation is sparse and dominated by xerophytic shrubs and trees and/or ephemeral grasses.

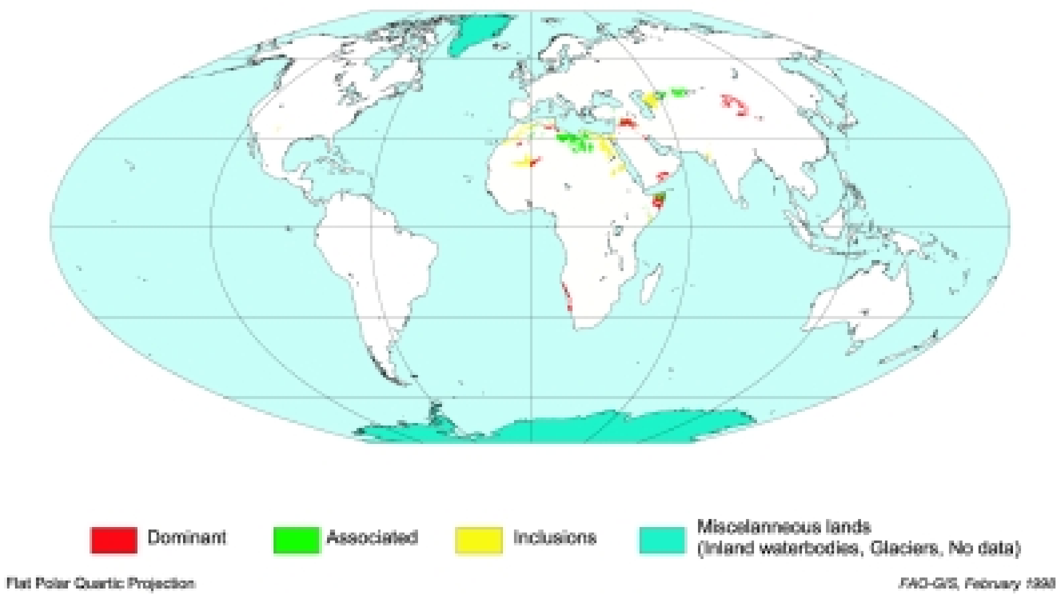
Profile development: AB(t)C profiles with a yellowish brown ochric surface horizon over a pale brown or whitish cambic or (relic ?) argic subsurface horizon. Accumulation of calcium sulphate, with or without carbonates, is concentrated in and below the B-horizon.

Use: Deep Gypsisols located close to water resources can be planted to a wide range of crops. Yields are severely depressed where a petrogypsic horizon occurs at shallow depth. Nutrient imbalance, stoniness, and uneven subsidence of the land surface upon dissolution of gypsum in percolating (irrigation) water are further limitations. Irrigation canals must be lined to prevent the canal walls from caving in. Large areas of Gypsisols are in use for low volume grazing.

Regional distribution of Gypsisols

Gypsisols are exclusive to arid regions; their world-wide extent is probably of the order of 100 million hectares. Major occurrences are in and around Mesopotamia, in desert areas in the Middle East and adjacent central Asian republics, in the Libyan and Namib deserts, in southeast and central Australia and in the southwestern USA. Figure 1 presents an overview of major Gypsisol areas.

Figure 1
Gypsisols world-wide



Associations with other Reference Soil Groups

Gypsisols occur in the same climatic zone as *Calcisols*. *Note that* presence of a gypsic or petrogypsic horizon is diagnostic for Gypsisols but that accumulation of gypsum occurs also in other Reference Soils. *Vertisols, Solonchaks, Gleysols* or *Kastanozems* with clear signs of gypsum accumulation intergrade with the Gypsisol Reference Group but do not key out as Gypsisols because of diagnostic properties other than a gypsic or petrogypsic horizon.

Genesis of Gypsisols

Most Gypsisols formed when gypsum, dissolved from gypsiferous parent materials, moved through the soil with the soil moisture and precipitated in an accumulation layer. Where soil moisture moves predominantly upward (i.e. where a net evaporation surplus exists for an extended period each year), a gypsic or petrogypsic horizon occurs at shallower depth than a layer with lime accumulation (if present). Gypsum is leached from the surface soil in wet winter seasons. In arid regions with hot, dry summers, gypsum ($CaSO_4.2H_2O$) dehydrates to loose, powdery hemihydrate ($CaSO_4.0.5H_2O$), which reverts to gypsum during the moist winter. The so-formed (highly irregular) gypsum crystals may cluster together to compact layers or surface crusts that can become tens of centimeters thick. Gypsum precipitates in the soil body as fine, white, powdery crystals in former root channels (*'gypsum pseudomycelium'*) or in pockets, or as coarse crystalline *'gypsum sand'*, or in strongly cemented *petrogypsic horizons*. In places it forms pendants below pebbles and stones or rosettes ('desert roses').

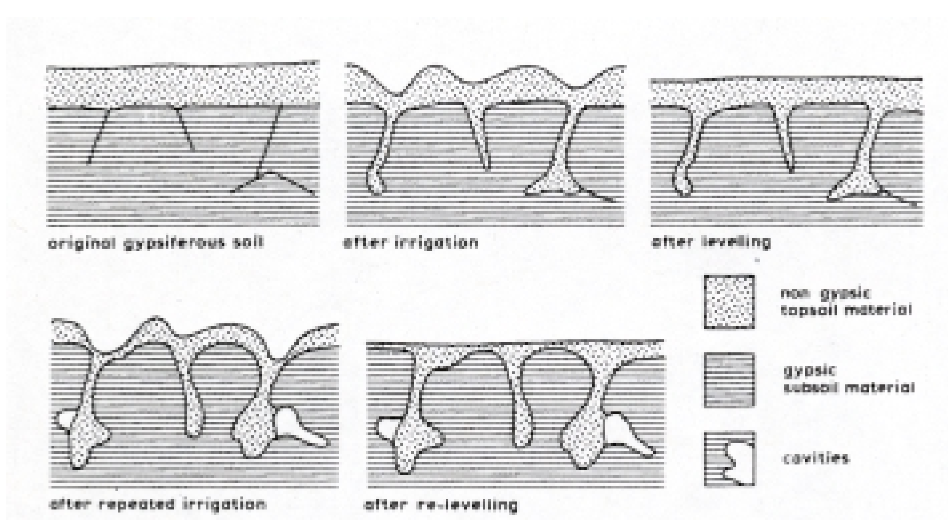
The accumulated gypsum is rarely formed *in situ*, but there are exceptions. 'Intrazonal' Gypsisols (formed under a dominant influence of *local* material or relief) have been reported from sites where sulphate-rich groundwater occurred at shallow depth. Another example was reported from areas with pyritic sediments in southwest Siberia where sulphate ions, formed when sulphides oxidized upon forced drainage of the land, precipitated as gypsum at depths of 20 to 150 cm below the surface of the soil. In the Republic of Georgia, gypsum was seen to form where saline, Na_2SO_4-containing, seepage water came in contact with dolomite weathering. By and large, however, the gypsum in Gypsisols originates from Triassic, Jurassic and Cretaceous evaporites or from (predominantly) Miocene gypsum deposits.

Characteristics of Gypsisols

Morphological characteristics

The 'typical' Gypsisol has 20 to 40 cm of yellowish brown, loamy or clayey surface soil over a pale brown subsurface soil with distinct white gypsum pockets and/or pseudo-mycelium. The surface layer consists of strongly de-gypsified weathering residues and has a low organic matter content and a weak, subangular blocky structure. Gypsum accumulation is most pronounced in the subsurface layer or slightly deeper and can be anything from a gypsic horizon with a soft, powdery and highly porous mixture of gypsum, lime and clay, to a hard and massive petrogypsic horizon of almost pure, coarse gypsum crystals.

Figure 2
Cavity formation, uneven subsidence, and stripping of the surface soil upon prolonged irrigation of shallow Gypsisols. Source: Van Alphen & Romero, 1971



Hydrological characteristics

Gypsisols feature a wide range of hydraulic properties. Saturated hydraulic conductivity values vary from 5 to >500 cm/d. Infiltration of surface water is almost zero in severely encrusted soils. By contrast, very high percolation losses occur in soils in which dissolution of gypsum has widened fissures, holes and cracks to interconnected subterranean cavities. Infilling of the cavities with surface soil material makes it necessary to level the land surface each year. This makes the valuable topsoil ever shallower. See Figure 2.

Physical characteristics

Most de-gypsified surface layers contain more than 40 percent clay and have an 'available' water holding capacity of 25 to 40 percent (by volume). Surface soils with more than 15 percent gypsum have seldom more than 15 percent clay and their retention of 'available' soil moisture does not exceed 25 volume percent.

Loamy surface soil slakes easily and subsequently dries to a finely platy crust at the surface that hinders infiltration of rainwater and promotes sheet wash and gully erosion.

Chemical characteristics

Small quantities of gypsum will not harm plants but gypsum contents of more than 25 percent, as common in gypsiferous subsoil, upset the nutrient balance and lower the availability of essential plant nutrients such as phosphorus, potassium and magnesium.

The *total* element contents of Gypsisol surface horizons are typically less than 2500 mg N/kg, 1000 mg P_2O_5/kg (of which less than 60 mg/kg is considered 'available'), and 2000 mg K_2O/kg: application of fertilizers is required for good yields. The cation exchange capacity (CEC) is conditioned by the clay content of the soil material; it is typically around 20 cmol(+)/kg in the surface soil and around 10 cmol(+)/kg deeper down. The exchange complex is saturated with bases.

Management and use of Gypsisols

Gypsisols that contain only little gypsum in the upper 30 cm soil layer can be used for production of small grains, cotton, alfalfa, etc. *Dry* farming on deep Gypsisols makes use of fallow years and other water harvesting techniques but is rarely rewarding under the adverse climate conditions. Many Gypsisols in (young) alluvial and colluvial deposits have relatively little gypsum. Such soils can be very productive if carefully irrigated. Even soils containing 25 percent powdery gypsum or more could still produce excellent yields of alfalfa hay (10 tons per hectare), wheat, apricots, dates, maize and grapes if irrigated at high rates in combination with forced drainage. Irrigated agriculture on Gypsisols is plagued by quick dissolution of soil gypsum resulting in irregular subsidence of the land surface, caving in canal walls, and corrosion of concrete structures. Dissolution of gypsum might also reduce the depth of a petrogypsic horizon to the extent that the hard pan obstructs root growth, and/or interferes with water supply to the crop and with soil drainage. Large areas with Gypsisols are in use for extensive grazing.

DURISOLS (DU)

The Reference Soil Group of the Durisols is represented in arid and semi-arid environments and holds very shallow to moderately deep, free-draining soils that contain cemented secondary silica (SiO_2) in the upper metre of soil. Durisols are internationally known as "hardpan soils" (Australia) or "dorbank" (South Africa) or they represent the "duripan phase" of other soils, e.g. of Calcisols (FAO).

Definition of Durisols#

Soils having a *duric*@ or *petroduric*@ horizon within 100 cm from the surface.

Common soil units**:**
Petric*, Leptic*, Vertic*, Gypsic*, Calcic*, Luvic*, Arenic*, Hyperduric*, Takyric*, Yermic*, Aridic*, Hyperochric*, Chromic*, Haplic*.

See Annex 1 for key to all Reference Soil Groups
@ Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Durisols

Connotation: soils with hardened secondary silica; from L. *durus*, hard.

Parent material: mainly alluvial and colluvial deposits of all texture classes.

Environment: level and slightly sloping alluvial plains, terraces and gently sloping piedmont plains in arid, semi-arid and Mediterranean regions.

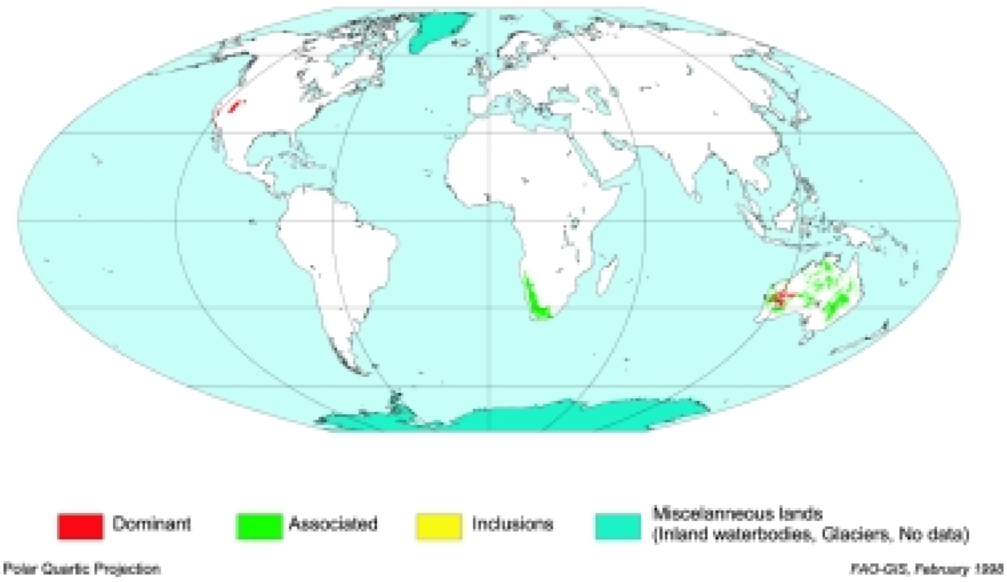
Profile development: AC or ABC profiles; eroded Durisols with exposed *petroduric* horizons are common in (gently) sloping terrain.

Use: most Durisols can only be used for extensive grazing. Arable cropping of Durisols is limited to areas where irrigation water is available (a continuous petroduric horizon at shallow depth must be broken up).

Regional distribution of Durisols

Extensive areas of Durisols occur in Australia, in South Africa/Namibia and in the USA (notably in Nevada, California and Arizona); minor occurrences have been reported from Central and South America and from Kuwait. Durisols are a new introduction in international soil classification and have not often been mapped as such. A precise indication of their extent is not (yet) available. Figure 1 presents a sketch map of their main occurrences.

Figure 1
Durisols world-wide



Associations with other Reference Soil Groups

Durisols are confined to dry regions, where they occur in association with *Gypsisols, Calcisols, Solonchaks, Solonetz, Vertisols, Arenosols, Cambisols* and, more rarely, *Planosols* or *Kastanozems*. In places, Durisols occur together with *Andosols*. In areas with silica-capped mesas, Durisols may be found in lower parts of the landscape.

Genesis of Durisols

Most Durisols occur in strongly weathered alluvial or colluvial parent material. It is generally believed that *duric* and *petroduric* horizons form by downward translocation of clay and silica, even in regions with a very low annual rainfall sum. Periodic flooding and wetting of the surface soil during occasional heavy downpours promote leaching and acidification of the upper soil layer; the leached silica accumulates deeper in the soil where it hardens as the soil dries out. The consistent occurrence of a cemented hardpan (a petroduric horizon, often referred to as a *'duripan'*) at shallow depth, even beneath surfaces on which new soil material regularly accumulates, is accepted as evidence that silica translocation is still taking place. The consistent positive correlation between the depth of the hardpan and the permeability of the overlying soil is a further indication that hardpan formation is not a paleo-feature.

Duric and petroduric horizons, with their active cementation, must not be confused with *'silcrete'*, i.e. hardened, silica-cemented lumps or continuous layers of soil material that formed under a different climate than that of today. Most silcrete stems is of (early) Tertiary age. It is commonly associated with silica-rich parent rocks such as quartz sandstone, but occurs also on weathered igneous rocks, and in the lower layers of strongly leached, red, tropical soils. In places, silcrete has become exposed after erosion of the surface soil; the hardened silcrete cap protects the soil from further erosion.

Characteristics of Durisols

Morphological characteristics

Most Durisols are well-drained, medium to coarse-textured soils. They have either a petroduric horizon or a duric horizon within 100 cm from the surface. A petroduric horizon is a subsurface horizon cemented by secondary silica (presumably amorphous and microcrystalline forms of SiO_2), commonly with accessory cements such as calcium carbonate and/or iron oxides. A duric horizon contains indurated nodules, ('*durinodes*') that are cemented by silica. Dry fragments of a petroduric or duric horizon do not slake upon prolonged soaking in water or in hydrochloric acid.

Petroduric horizons range in thickness from 10 cm to more than 4 m. Two main morphological types are distinguished, i.e. massive '*duripans*', and 'duripans' with a platy or laminated structure. The plates or *'laminae'* are between a few mm and 15 cm thick. Pores and surfaces of plates are coated with amorphous *'opal'* or microcrystalline silica. Roots tend to grow in between the plates or form a mat on top of the petroduric horizon. Rodents are capable of burrowing through the pan(s); their burrows are later filled in with soil material from shallower horizons. Roots and water can enter the underlying horizons through these passages, which improve root growth and soil moisture retention.

The 'durinodes' in a duric horizon show normally a pattern of roughly concentric layers when viewed in cross section. Duric horizons are less common than petroduric horizons of which they are considered to be the predecessor.

A typical Durisol profile has a red (brown) to grayish brown, non-calcareous surface soil on top of a duric or petroduric horizon. Durisols may have an argic, cambic or calcic horizon above the (petro)duric horizon. If unconsolidated materials underlie the (petro)duric horizon, these are normally weakly structured and calcareous or gypsiferous. In many instances the material is calcareous immediately below the (petro)duric horizon and gypsiferous at greater depth.

Hydrological characteristics

The water storage capacity of Durisols with a petroduric horizon depends mainly on the depth and composition of the soil above this *'duripan'*. The petroduric horizon obstructs vertical water movement. Data on soil moisture stored between 333 and 15,000 hPa soil suction (often wrongly perceived as 'available' soil moisture), suggest that any value between (almost) 0 and 15 % moisture may be expected. In less strongly cemented duric horizons one may find between 5 and 15 % 'available' moisture.

Physical characteristics

The texture class of petroduric and duric horizons can range from sand to sandy clayloam. Textures finer than sandy clayloam are rare; sandy loam appears to be the most common material. The bulk density of petroduric and duric horizons is between 1.2 and 2.0 kg dm^{-3}; values between 1.3 and 1.7 kg dm^{-3} are most common. Petroduric horizons tend to be denser (bulk density between 1.6 and 2.0 kg dm^{-3}) than duric horizons.

Petroduric and duric horizons are normally (but not exclusively) 'massive', i.e. without structure. The dry consistence of 'duripans' is typically hard or extremely hard. The dry consistence of duric horizons varies between soft and very hard but 'durinodes' are usually (extremely) hard.

Chemical characteristics

The $pH_{(H2O)}$ of petroduric and duric horizons may be as low as 5.0 or as high as 10.0 but values are typically between 7.5 and 9.0. The electrical conductivity is typically less than 4 dS m^{-1}; higher values are not uncommon ("Hyposalic" and "Salic" soil units). Many Durisols have high levels of exchangeable sodium and low contents of carbon and extractable iron. The (nominal) base saturation is usually well in excess of 50 %.

Land use and management of Durisols

The agricultural use of Durisols is limited to extensive grazing. Durisols in 'natural' environments generally support enough vegetation to contain erosion but elsewhere erosion of the surface soil is widespread.

Stable landscapes occur in dry regions where Durisols were eroded down to their resistant 'duripan'. Durisols may be cultivated with some success if sufficient irrigation water is available. Note that the petroduric horizon must be broken up, or removed altogether, if it forms a barrier to root and water penetration. Excess levels of soluble salts may build up in Durisols in low-lying areas. Hard 'duripan' material is used in road construction.

CALCISOLS (CL)

The Reference Soil Group of the Calcisols accommodates soils in which there is substantial secondary accumulation of lime. Calcisols are common in calcareous parent materials and widespread in arid and semi-arid environments. Formerly Calcisols were internationally known as 'Desert soils' and 'Takyrs'.

Definition of Calcisols#

Soils having
1. a *calcic*@ or *petrocalcic*@ horizon within 100 cm of the surface; ***and***
2. no diagnostic horizons other than an *ochric*@ or *cambic*@ horizon, an *argic*@ horizon which is calcareous, a *vertic*@ horizon, or a *gypsic*@ horizon.

Common soil units:
Petric*, Hypercalcic*, Leptic*, Vertic*, Endosalic*, Gleyic*, Luvic*, Takyric*, Yermic*, Aridic*, Hyperochric*, Skeletic*, Sodic*, Haplic*.

See Annex 1 for key to all Reference Soil Groups
@ Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Calcisols

Connotation: soils with substantial secondary accumulation of lime; from L. *calcarius*, calcareous

Parent material: mostly alluvial, colluvial and aeolian deposits of base-rich weathering material.

Environment: level to hilly land in arid and semi-arid regions. The natural vegetation is sparse and dominated by xerophytic shrubs and trees and/or ephemeral grasses.

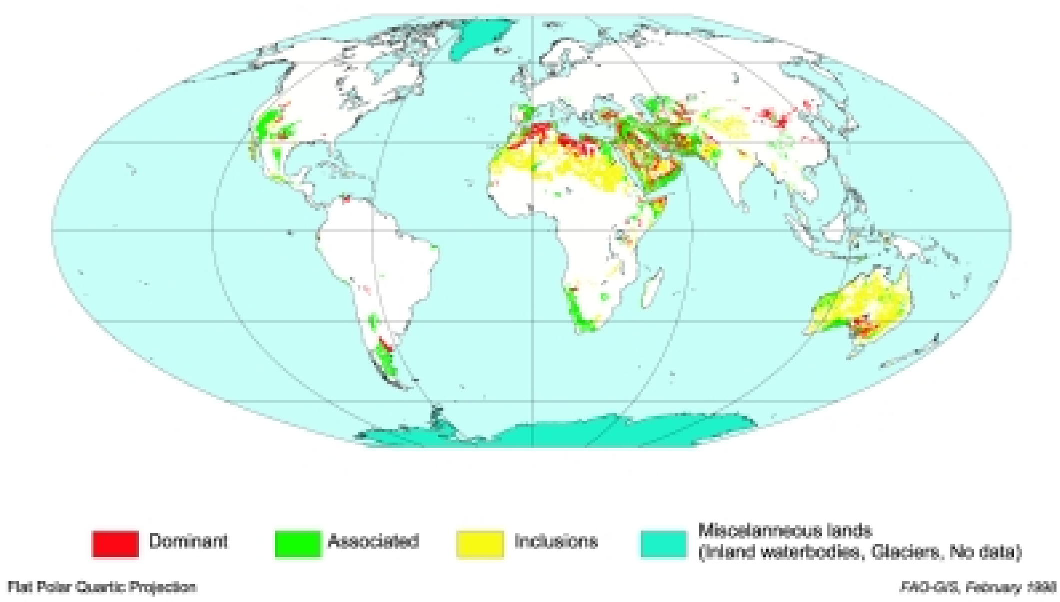
Profile development: 'typical' Calcisols have ABC or AB(t)C-profiles with a pale brown ochric surface horizon over a cambic or argic subsurface horizon. Finely textured subsurface horizons may develop some or all of the characteristics of a vertic horizon. Substantial secondary accumulation of lime occurs within 100 cm from the surface.

Use: dryness, and in places also stoniness and/or the presence of a shallow petrocalcic horizon, limit the suitability of Calcisols for agriculture. If irrigated, drained (to prevent salinisation) and fertilised, Calcisols can be highly productive under a wide variety of crops. Hilly areas with Calcisols are predominantly used for low volume grazing of cattle, sheep and goats.

Regional distribution of Calcisols

It is difficult to quantify the worldwide extent of Calcisols with any measure of accuracy. Many Calcisols occur together with Solonchaks that are actually salt-affected Calcisols and/or with other soils with secondary accumulation of lime that do not key out as Calcisols. The total Calcisol area may well amount to some 1 billion hectares, nearly all of it in the arid and semi-arid (sub)tropics of both hemispheres. Figure 1 gives an indication of the regional distribution of Calcisols.

Figure 1
Calcisols world-wide



Associations with other Reference Soil Groups

Calcisols can occur in association with a variety of soils, many of them with signs of secondary redistribution of carbonates. Lateral transitions in the field are primarily associated with differences in relief, climate and/or geology. Cross-sections through landscapes with Calcisols normally show a gradual transition from shallow soils with rather diffuse signs of lime redistribution (at the highest parts) to deeper soils that are also richer in carbonates. There is great variation in the expression of lime redistribution; common forms include filled-in pores that show up as *'pseudomycelia'*, pockets of soft lime, soft and hard nodules, and layered, platy or compact, consolidated *'calcrete'*. Studies of calcic horizons suggest that both lateral and vertical redistribution of lime have occurred and that lateral movement of lime is not without significance. Soils found in association with Calcisols range from shallow *Leptosols* (at the highest parts of the landscape) to *Vertisols* at the lower end of slopes and in bottomlands. Calcisols in depression areas are frequently associated with *Solonchaks* and *Gleysols*. Piedmont plains with Calcisols in semi-arid subtropical regions may grade into areas with *Chernozems* or *Kastanozems* with a deep groundwater table.

Genesis of Calcisols

Many Calcisols are old soils if counted in years but their development was slowed down by recurrent periods of drought in which such important soil forming processes as chemical weathering, accumulation of organic matter and translocation of clay came to a virtual standstill. As a result, only an ochric surface horizon could develop and the modification of subsoil layers did not advance beyond the formation of a cambic subsurface horizon. Many Calcisols are *'polygenetic'*: their formation took different courses during different geologic eras with different climates. The argic subsurface horizon of many Calcisols is widely considered to be a relic from eras with a more humid climate than at present.

The most prominent soil forming process in Calcisols - the process from which the soils derived their name - is the translocation of calcium carbonate from the surface horizon to an accumulation layer at some depth. In eroding land or in land that is intensively homogenised by burrowing animals, lime concretions may occur right at the surface of the soil. However, it is more common to find the surface horizon wholly or partly de-calcified.

Dissolution of calcite ($CaCO_3$) and subsequent accumulation in a *calcic* or *petrocalcic* horizon is governed by two factors:

1. the *CO_2-pressure* of the soil air, and
2. the *concentrations of dissolved ions* in the soil moisture.

The following equilibria are involved (the pH-ranges over which the equilibria are in operation are shown in Figure 2):

$$CO_2 + H_2O = H_2CO_3^o$$

$$H_2CO_3^o = HCO_3^- + H^+$$

$$HCO_3^- = CO_3^{2-} + H^+$$

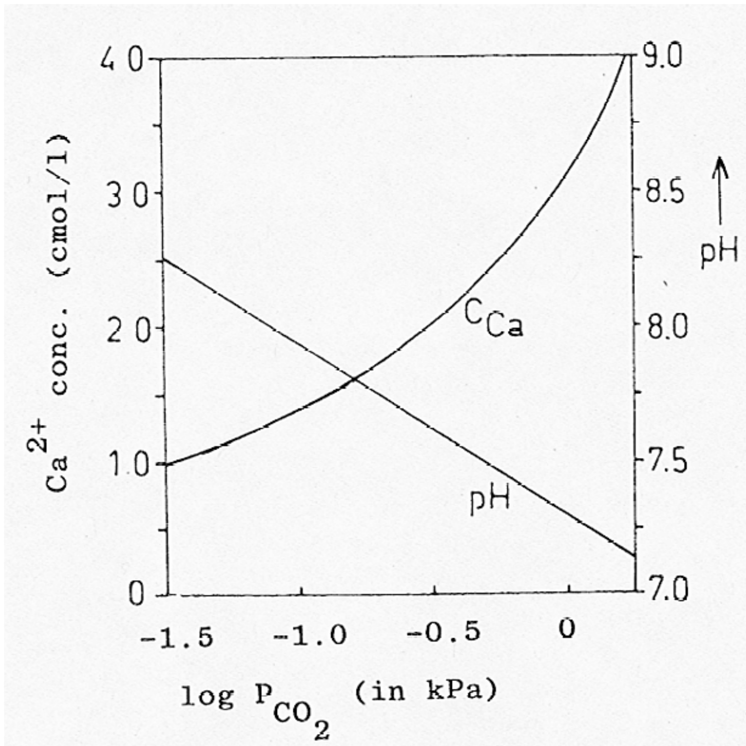
For all practical purposes, the dissolution and precipitation of calcite in soils (pH <9) can be viewed as follows:

$$CaCO_3 + H_2CO_3 = Ca^{2+} + 2\ HCO_3^-$$

An increase in the CO_2-content of the soil-air drives the reaction to the right: calcite dissolves and the concentrations of Ca^{2+}- and HCO_3^--ions in the soil solution rise. Alternatively, calcite dissolves if (rain) water with a low Ca^{2+}-concentration flushes the soil.

Precipitation of calcite occurs if the reaction is driven to the left, e.g. by a lowering of the CO_2-pressure (with a consequent rise in pH), or by an increase in ion concentrations to the point where the solubility product of dissolved calcium carbonate is exceeded.

Figure 2
Solubility of calcite at different CO_2-pressures and corresponding pH-values.
Source: Bolt & Bruggenwert, 1979



The formation of a *calcic* horizon is now easily understood: the partial CO_2-pressure of the soil-air is normally highest in the A-horizon where root activity and respiration by micro-organisms cause CO_2 contents to be 10 to 100 times higher than in the atmospheric air. As a consequence, calcite dissolves and Ca^{2+}- and HCO_3^--ions move downward with percolating soil moisture, particularly during and directly after a rain shower. The water may take up more dissolved calcite on its way down.

Evaporation of water and a decrease in partial CO_2-pressure deeper in the profile (fewer roots and less soil organic matter and microorganisms) cause saturation of the soil solution and precipitation of calcite. The precipitated calcite is not or only partly transported back with ascending water because much of this water moves in the vapour phase. (The water table in Calcisols is normally deep; where there is capillary rise to the solum, calcite accumulates at the depth where the capillary water evaporates.)

Calcite precipitation is not (always) evenly distributed over the soil matrix. Root channels and wormholes that are connected with the outside air act as ventilation shafts in which the partial CO_2-pressure is much less than in the soil around it. When $Ca(HCO_3)_2$-containing soil moisture reaches such a channel, it loses CO_2 and calcite precipitates on the channel walls.

Where narrow root channels become filled with calcite, so-called *'pseudomycelium'* forms. Other characteristic forms of calcium carbonate accumulation in Calcisols are *nodules* of soft or hard lime (*'calcrete'*), platy or continous layers of calcrete and calcite *'pendants'* or 'beards' below pebbles.

High soil temperature and high soil-pH enhance dissolution of silica from feldspars, ferromagnesian minerals, etc. Where there is (or was) sufficient moisture in some period of the year to enable translocation of dissolved silica, this may have furthered the hardening of the layer with calcite accumulation. However, cementation of a petrocalcic horizon is in first instance by calcium and magnesium carbonates.

CHARACTERISTICS OF CALCISOLS

Morphological characteristics

Most Calcisols have a thin (=<10 cm) brown or pale brown surface horizon over a slightly darker subsurface horizon and/or a yellowish brown subsoil that is speckled with white calcite mottles. The organic matter content of the surface soil is low, in line with the sparse vegetation and rapid decomposition of vegetal debris. The surface soil is crumb or granular, but platy structures can occur as well, possibly enhanced by a high percentage of adsorbed magnesium. Most subsurface soils have a blocky structure; the structure elements are coarser, stronger and often more reddish in colour in an argic horizon than in subsurface soils without clay accumulation.

The highest calcite concentration is normally found in the deeper subsurface soil and in the subsoil. Burrowing animals homogenize the soil and bring hardened carbonate nodules to the surface; their filled-in burrows *('krotovinas')* may extend deep into the subsoil.

Hydrological characteristics

Most Calcisols are well drained and are wet only in part of the (short) rainy season when there is just enough downward percolation to flush soluble salts to the deep subsoil. One reason why Calcisols as a taxonomic unit have good drainage properties is that carbonate-rich soils in wet positions (depressions, seepage areas) quickly develop a *salic* horizon (long dry summers!) and key out as Solonchaks.

Physical characteristics

Most Calcisols have a medium or fine texture and good water holding properties. Slaking and crust formation may hinder the infiltration of rain and irrigation water, particularly where surface soils are silty. Surface run-off over the bare soil causes sheet wash and gully erosion and, in places, exposure of a petrocalcic horizon.

Chemical characteristics

Most Calcisols contain only 1 or 2 percent organic matter but many are rich in plant nutrients. The $pH_{(H2O;1:1)}$ is near-neutral in the surface soil and slightly higher at a depth of 80 to 100 cm where the carbonate content may be 25 percent or more. The nominal cation exchange capacity of typical Calcisols is highest in the surface soil (10 to 25 cmol(+)/kg) and slightly less at some depth. The exchange complex is completely saturated with bases; Ca^{2+} and Mg^{2+} make up more than 90 percent of all adsorbed cations.

Land use and management of Calcisols

Vast areas of 'natural' Calcisols are under shrubs, grasses and herbs and are used for extensive grazing. Drought-tolerant crops such as sunflower might be grown rain-fed, preferably after one or a few fallow years, but Calcisols reach their full productive capacity only when carefully irrigated. Extensive areas of Calcisols in the Mediterranean zone are used for production of irrigated winter wheat, melons, and cotton. Fodder crops such as 'el sabeem' (*sorghum bicolor*), Rhodes grass and alfalfa, are tolerant of high calcium levels. A score of vegetable crops have successfully been grown on irrigated Calcisols fertilised with nitrogen, phosphorus and trace elements (Fe, Zn).

Furrow irrigation is superior to basin irrigation on *slaking* Calcisols because it reduces surface crusting/caking and seedling mortality; pulse crops in particular are very vulnerable in the seedling stage. In places, arable farming is hindered by stoniness of the surface soil and/or a petrocalcic horizon at shallow depth. Citrus is reportedly sensitive to high levels of *'active* $CaCO_3$*'* i.e. finely divided calcium carbonate particles in the soil matrix.

Set #8

Mineral Soils conditioned by a Steppic Climate

Major landforms in steppe regions
Chernozems
Kastanozems
Phaeozems

Major landforms in steppe regions

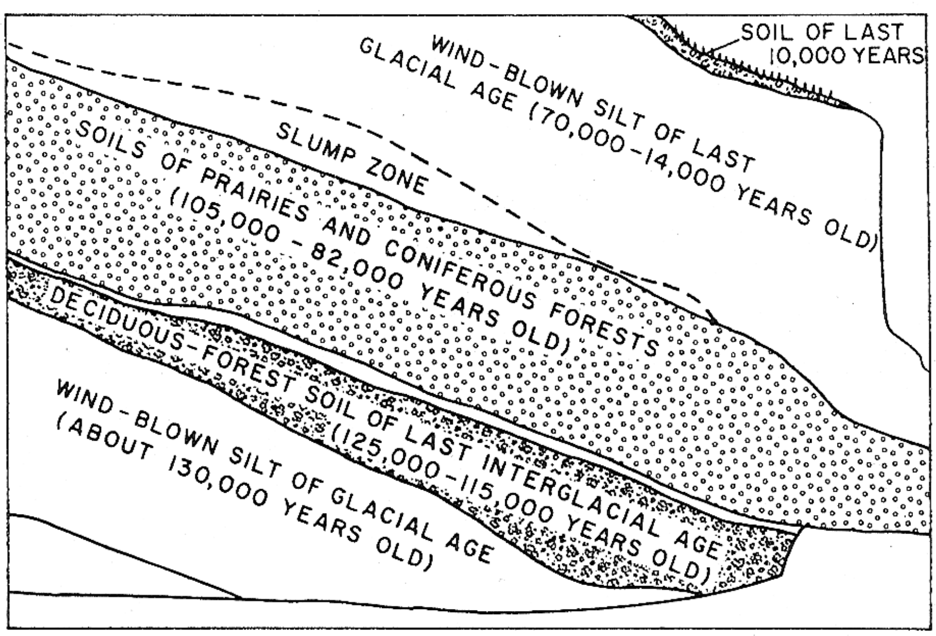
Steppes and steppic regions (pampas, prairies) receive between 250 and 500 mm of precipitation annually, i.e. more than twice the quantity that falls in true desert areas where rainfall is insufficient to support a vegetation that could protect the land from erosion.

Dunes and sand plains form where strong winds carry sand grains 'in saltation' over short distances. Particles finer than sand are transported 'in suspension' and over greater distances until they settle as *'loess'*, predominantly in the steppe regions adjacent to the desert zone.

Landforms in regions with loess

Chinese records make mention of extensive loess deposition between 400 and 600 AD, between 1000 and 1200 AD and between 1500 and 1900 AD (during the 'Little Ice Age'). However, the most extensive occurrences of loess on Earth (in the steppe regions of Eastern and Central Europe and the USA) are of Pleistocene age (see Figure 1).

Figure 1
Climatic history recorded in a brickyard in Czechia. Events of the past 130,000 years are visible in a quarry at Nove Mesto. (Based on the work of G.J. Kukla.)

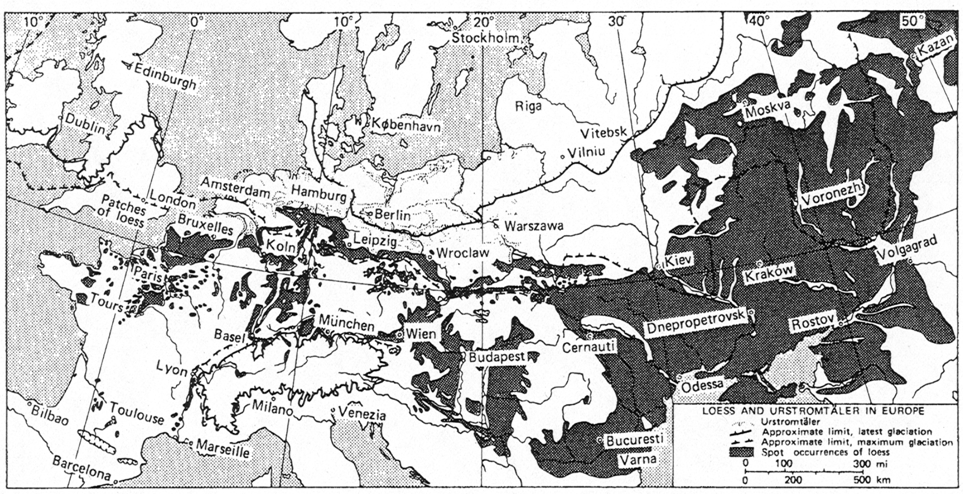


For good understanding of landforms and soils in steppe regions it is important that one understands the relation between Ice Age aridity and loess deposition.

During the Late Pleniglacial, between 20,000 and 13,000 BP, some 25 percent of the land surface became covered with continental ice sheets (versus some 10 percent today). With so much water stored in ice sheets, the sea level dropped to about 120 metres below the present level and large parts of the world became extremely arid. The Amazon rain forest dwindled to isolated refugia, European forests disappeared but for small sheltered areas, and large parts of the globe turned to tundra, steppe, savannah or desert.

Clearly, aeolian processes were much more important at that time than at present. Large parts of the present temperate zone, from the ‘cover sands’ of the Netherlands to the sand dunes in north-east Siberia are Ice Age (aeolian) sands. South and east of this cover sand belt lies a belt of loess deposits, extending from France, across Belgium, the southern Netherlands, Germany and large parts of Eastern Europe into the vast steppes of Russia, and further east to Siberia and China. See Figure 2. A similar east-west loess belt exists in the USA and less extensive areas occur on the Southern Hemisphere, e.g. in the Argentinean pampas.

Figure 2
Distribution of loess in Europe. Source: Flint, 1971



Loess is a well sorted, usually calcareous, non-stratified, yellowish-grey, aeolian clastic sediment. It consists predominantly of silt-sized particles (2-50 mm), and contains normally less than 20 percent clay and less than 15 percent sand. It covers the land surface as a blanket, which is less than 8 metres thick in the Netherlands (exceptionally 17 metres) but can reach up to 40 metres in Eastern Europe and 330 metres in China.

Loess is very porous material and vertical walls remain remarkably stable, but loess slakes easily so that exposed surface areas are prone to water erosion. The loess material itself is produced by abrasion of rock surfaces by glaciers and blown out from glacial outwash plains and alluvium. It is generally difficult to identify the exact source areas of specific loess deposits because the various loess deposits have a surprisingly similar mineralogy. 'Typical' loess contains quartz, feldspar, some micas, calcium carbonate and clay minerals. A possible explanation may be that glaciers abrade large surfaces of diverse mineralogy, so that the mineralogical variation between different source areas is averaged out. Further mixing and homogenisation of dust particles from various sources occurs during transport. Loess is absent from regions that were covered by glaciers in the *last* glacial period, nor does it occur in the humid tropics. The vast areas of loess in China may not have a glacial origin: the loess grades into the sandy loess and sands of the Gobi desert in Mongolia. Deposition is still going on today at a rate of several millimetres per year. Long-distance transport of dust particles from the Gobi desert seems to be responsible for the thick Chinese loess deposits.

The aeolian origin of loess is evidenced by the following facts:

1. loess occurs as *a blanket over a wide range of surfaces*, to a large extent independent of topography;
2. loess *blankets are thickest on the leeward sides of obstacles*;
3. there is absolutely *no (cor)relation between the mineralogy* of the loess blanket and that of subsurface strata (which rules out the possibility of in-situ weathering);
4. the *grain-size distribution of loess is typical of material transported in suspension*;
5. grain sizes show a *downwind fining gradient*, away from the source;
6. loess *deposits become thinner away from their presumed source*;
7. fossil *terrestrial (sic!) snails have been found in loess deposits*;
8. intercalated *'paleosols'* (fossil soils) are common in most loess belts;
9. loess *deposition still happens around desert areas today*.

Loess settles when dust-laden winds slow down to speeds between 7 (on dry surfaces) to 14 meters per second (on moist surfaces). The pore distribution of loess lets it quickly be retained by capillary forces if it lands on a moist surface. The presence of a vegetation cover may also enhance the rate of loess deposition, and many authors maintain that the northern limit of loess deposition coincides with the northernmost extent of grass steppes during arid periods in the Pleistocene.

It has already been said that small-scale stratification is usually absent from loess because of the extreme uniformity in grain size. Laminated 'loessoid' deposits are the products of post-depositional sheet wash. Larger-scale layering, (deci)metres thick, suggests a certain periodicity in loess deposition. At least two separate loess sequences were identified in the Netherlands, a Weichselian one, and an older, Saalian sequence. The boundary between the two sequences is marked by the occurrence of a relic soil profile that developed in the Saalian loess during the Eemian interglacial period.

Landforms in regions without loess

Vast undulating till plains occur in North America, between the Canadian shield area and the loess belt. This area is either covered with thick tills or with 'deglaciation' sediments, lacustrine sediments in particular. The lake areas are level as such but the till landscape has a typical *'hummocky'* relief. The main characteristic of hummocky tills (40% of the total area) is the predominance of very local drainage patterns (mainly in depressions). Tills and loess have in common that they are internally uniform and that they all date back to deglaciation periods.

The vast loess and till plains are now colonised by grasses and/or forest. They are the home of some of the best soils of the world: the ‘black earths’. Deep, black Chernozems occupy the central parts of the Eurasian and North American steppe zones. Brown Kastanozems are typical of the drier parts of the steppe zone and border on arid and semi-arid lands. Dusky red Phaeozems occur in slightly more humid areas such as the American prairies and pampas.

CHERNOZEMS (CH)

The Reference Soil Group of the Chernozems accommodates soils with a thick black surface layer rich in organic matter. Russian soil scientist Dokuchaev coined the name “Chernozems” in 1883 to denote the typical “zonal” soil of the tall grass steppes in continental Russia. Some international synonyms: ‘Calcareous Black Soils’, ‘Eluviated Black Soils’ (Canada), and (several suborders of) ‘Mollisols’ (USDA Soil Taxonomy).

Definition of Chernozems[#]

Soils having,
1. a *mollic*[@] horizon with a moist chroma of 2 or less if the texture is finer than sandy loam, *or* less than 3.5 if the texture is sandy loam or coarser, both to a depth of at least 20 cm, *or* having these chromas directly below any plough layer; and
2. concentrations of *secondary carbonates*[@] starting within 200 cm from the soil surface; and
3. no *petrocalcic*[@] horizon between 25 and 100 cm from the soil surface; and
4. no secondary gypsum; and
5. no uncoated silt and sand grains on structural ped faces.

Common soil units:
Chernic*, Vertic*, Gleyic*, Calcic*, Luvic*, Glossic*, Siltic*, Vermic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Chernozems

Connotation: black soils rich in organic matter; from R. *chern*, black, and *zemlja*, earth or land.

Parent material: mostly aeolian and re-washed aeolian sediments (loess).

Environment: regions with a continental climate with cold winters and hot summers; in flat to undulating plains with tall-grass vegetation (forest in the northern transitional zone).

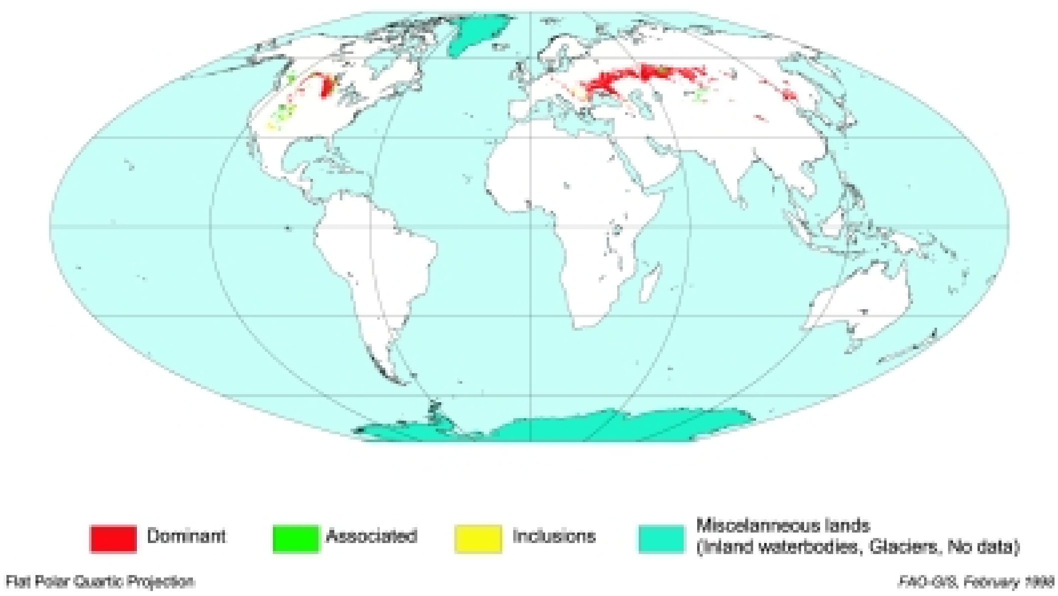
Profile development: AhBC profiles with a dark brown to black *mollic* surface horizon over a *cambic* or *argic* subsurface horizon, commonly with redistribution of calcium carbonate to a *calcic* horizon or pockets of *secondary carbonates* in the subsurface soil.

Use: the high natural fertility of Chernozems and their favourable topography permit a wide range of agricultural uses including arable cropping (with supplemental irrigation in dry summers) and cattle ranging.

Regional distribution of Chernozems

Chernozems cover an estimated 230 million hectares world-wide, mainly in the middle latitude steppes of Eurasia and North America, north of a zone with Kastanozems. Figure 1 presents an overview of their main areas of occurrence.

Figure 1
Chernozems world-wide



Associations with other Reference Soil Groups

Chernozems in Russia (north of the Ural range) and in North America are associated with *Luvisols, Albeluvisols* and Greyic *Phaeozems* towards the cool northern border of the steppe zone and grade into *Kastanozems* towards the warm and dry south. Where the Chernozem belt borders on warm, humid regions, Chernozems may grade into Phaeozems.

Genesis of Chernozems

The 'typical' Chernozem has formed in uniformly textured, silty parent material (loess), under tall-grass vegetation with vigorous growth. The above ground biomass amounts to some 1 to 1.5 tons of dry matter per hectare; the corresponding root mass, already incorporated in the soil, weighs 4 to 6 tons/hectare. The main concentration of roots is in the upper 60 cm of soil, with 80 percent of all roots concentrated in the top 30 to 40 cm.

Deep, humus-rich Chernozems occur in the central part of the steppe zone where the annual precipitation sum is approximately equal to the evaporation sum. Such soils contain 10 to 16 percent organic matter in their surface layers, are neutral in reaction (pH 7.0, and around 7.5 in the subsoil), and highly saturated with bases. Soil fauna is very active in Chernozems, in wet periods predominantly in the upper 50-cm layer but the animals move to deeper strata at the onset of the dry period. Vermic Chernozems consist for the greater part of worm casts, a stable mixture of mineral and organic soil material. Burrowing small vertebrates contribute significantly to intense homogenization (*'bioturbation*') of the soil. Animal burrows that became filled-in with humus-rich surface soil stand out as black '*krotovinas*' (from R. *krot*, a Eurasian mole, *Talpa europaea*) against the typically cinnamon coloured deeper soil matrix.

The high porosity and favourable structure of the deep, homogenized Ah-horizon explain why deep percolation of rainwater during wet spells is sufficient to flush virtually all readily soluble salts from the soil. There may be some accumulation of gypsum at a depth of 2 to 3 meters from the soil surface (1.5 to 2.5 m in southern Chernozems), and accumulation of lime at a shallower depth, say at about 1 metre from the soil surface. A *'dead dry horizon*' may be present at a depth of about 4 metres, deeper in the north of the Chernozem belt than in the south. This soil layer receives neither percolation water from above nor capillary rise from below. The dead dry horizon needs not to be continuous; its thickness varies and it can even be absent altogether.

Migration of clay has resulted in slightly increased clay contents between 50 to 200 cm from the surface in many Chernozems in the central steppe zone. This indicates that central Chernozems are exposed to moderately strong leaching during wet periods.

Northern Chernozems are subject to stronger leaching than those of the central steppe zone.

Towards the northern fringe of the Chernozem belt, the surface horizon becomes shallower, more acid (pH 6-6.5) and more greyish until signs of podzolization such as an ash-grey eluvial subsurface horizon and/or horizontal lamellae in the subsoil become evident. In northern Chernozems, the horizon with carbonate accumulation is normally separated from the humus-rich surface layer by a carbonate-free layer of appreciable thickness.

Towards the southern fringe of the steppe zone, the water regime becomes more and more intermittent, with increasingly longer dry periods. Consequently, plants with a long vegetative period disappear and xerophytes and ephemeral grasses move in. Also, the soil's humus undergoes more intense mineralization and there is an increase in the content of readily soluble salts in the surface soil.

Note that the colour of the surface soil has diagnostic value: where the chroma of the upper 20 cm of soil has become more than 2, this is seen as a sign that aridity is so severe that the soils are no longer true Chernozems. They are then classified as Kastanozems.

Characteristics of Chernozems

Morphological characteristics

Virgin Chernozems have a thin leafy litter layer on top of a dark grey to black, crumb, '*vermic*' Ah-horizon. The surface horizon can be only 20 cm thick but extends down to a depth of more than 2 metres in well-developed Chernozems. Worm casts and krotovinas testify of intense faunal activity.

Calcium carbonate accumulation in the lower part of the surface soil is common, secondary carbonates occur as *pseudo-mycelium* and/or *nodules* in a brownish grey to cinnamon subsoil. The subsurface horizon has blocky or weakly prismatic structure.

The grass vegetation grades into deciduous forest towards the north of the Chernozem belt where the Ah-horizon may overly an argic B-horizon (Luvic Chernozems) or even tongue into the B-horizon (Glossic Chernozems). There, Chernozems grade into Luvisols or Albeluvisols. Many Chernozems in wet areas develop signs of hydromorphy (Gleyic Chernozems, known as 'Meadow Chernozems' in Russia and most of Eastern Europe).

Mineralogical characteristics

The mineral composition of Chernozems is rather uniform throughout the profile, in line with the high rate of homogenization of the soil material. The SiO_2/R_2O-ratio is high, at about 2.0.

Hydrological characteristics

Although it is widely accepted that Chernozems formed under conditions of good drainage, there are also (Russian) soil scientists who maintain that certain Chernozems passed through a boggy phase of soil formation. Today's Chernozems are well drained, apart from soils in depressions with occasional shallow groundwater. By and large, there is approximate equity between the annual precipitation sum and evaporation, with a slight precipitation surplus in the north of the steppe zone and a slight deficit in the south. Table 1 presents an overview of the occurrence of Eurasian steppe soils in relation with the annual precipitation sum and the type of vegetation.

TABLE 1
Typical Reference Soil Groups in the Eurasian steppe zone

Temperature	Precipitation	Vegetation	Reference Soil Group/Unit
	>550 mm	deciduous forest	Luvisols, Albeluvisols, Phaeozems
	500 mm	**steppe and forest**	**Luvic Chernozem**
	500 mm	**tall grass steppe**	**Haplic Chernozem**
increase	**450 mm**	**tall grass steppe**	**Calcic Chernozem**
	200-400 mm	medium height grass steppe	Kastanozems
↓	< 200 mm	open vegetation	Calcisols

Physical characteristics

Chernozems possess favourable physical properties. The total pore volume of the Ah-horizon amounts to 55 to 60 volume percent and that of the subsoil lies between 45 and 55 percent. Chernozems have good moisture holding properties; reported soil moisture contents of some 33 percent at *'field capacity'* and 13 percent at *'permanent wilting point'* suggest an *'available water capacity'* (AWC) of some 20 volume percent. The stable micro-aggregate structure ('crumb') of the humus-rich Ah-horizon represents a favourable combination of capillary and non-capillary porosity and makes these soils highly suitable for irrigated farming.

Chemical characteristics

Chernozem surface soils contain between 5 and 15 percent of 'mild' humus with a high proportion of humic acids and a C/N-ratio that is typically around 10. The surface horizon is neutral in reaction (pH 6.5-7.5) but the pH may reach a value of 7.5-8.5 in the subsoil, particularly where there is accumulation of lime. Chernozems have good natural fertility; the surface soil contains 0.2-0.5 percent nitrogen and 0.1 to >0.2 percent phosphorus. This phosphorus is only partly 'available'; crops on Chernozems tend to respond favourably to application of P-fertilizers. In southern Chernozems, humus contents are lower (4-5 percent) and consequently also the cation exchange capacity: 20-35 cmol(+)/kg dry soil, versus 40-55 cmol(+) per kg in central Chernozems. Normally, the base saturation percentage is close to 95 percent with Ca^{2+} and Mg^{2+} as the main adsorbed cations but sodium adsorption may be high in southern Chernozems.

Management and use of Chernozems

Russian soil scientists rank the deep, central Chernozems among the best soils in the world. With less than half of all Chernozems in Eurasia being used for arable cropping, these soils constitute a formidable resource for the future.

Preservation of the favourable soil structure through timely cultivation and careful irrigation at low watering rates prevents ablation and erosion. Application of P-fertilizers is required for high yields. Wheat, barley and maize are the principal crops grown, alongside other food crops and vegetables. Part of the Chernozem area is used for livestock rearing. In the northern temperate climatic belt, the possible growing period is short and the principal crops grown are wheat and barley, in places in rotation with vegetables. Maize is widely grown in the warm temperate belt. Maize production tends to stagnate in drier years unless the crop is adequately irrigated.

KASTANOZEMS (KS)

The Reference Soil Group of the Kastanozems holds the 'zonal' soils of the short grass steppe belt, south of the Eurasian tall grass steppe belt with Chernozems. Kastanozems have a brownish humus-rich surface horizon (less deep and less black than that of the Chernozems) and they show prominent accumulation of secondary carbonates in the sub(surface) soil. The chestnut-brown colour of the surface soil gave these soils their name 'Kastanozem'; common international synonyms are '(Dark) Chestnut Soils' (Russia), (Dark) Brown Soils (Canada), and Ustolls and Borolls in the Order of the Mollisols (USDA Soil Taxonomy).

Definition of Kastanozems[#]

Soils having,

1. a *mollic*[@] horizon with a moist chroma of more than 2 to a depth of at least 20 cm, or having this chroma directly below the depth of any plough layer, and
2. concentrations of *secondary carbonates*[@] within 100 cm from the soil surface, and
3. no diagnostic horizons other than an *argic*[@], *calcic*[@], *cambic*[@], *gypsic*[@], *petrocalcic*[@], *petrogypsic*[@] or *vertic*[@] horizon.

Common soil units:
Anthric*, Vertic*, Petrogypsic*, Gypsic*, Petrocalcic*, Calcic*, Luvic*, Hyposodic*, Siltic*, Chromic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Kastanozems

Connotation: (dark) brown soils rich in organic matter; from L. *castanea*, chestnut, and from R. *zemlja*, earth, land.

Parent material: a wide range of unconsolidated materials. A large part of all Kastanozems have developed in loess.

Environment: dry and warm; flat to undulating grasslands with ephemeral short grasses.

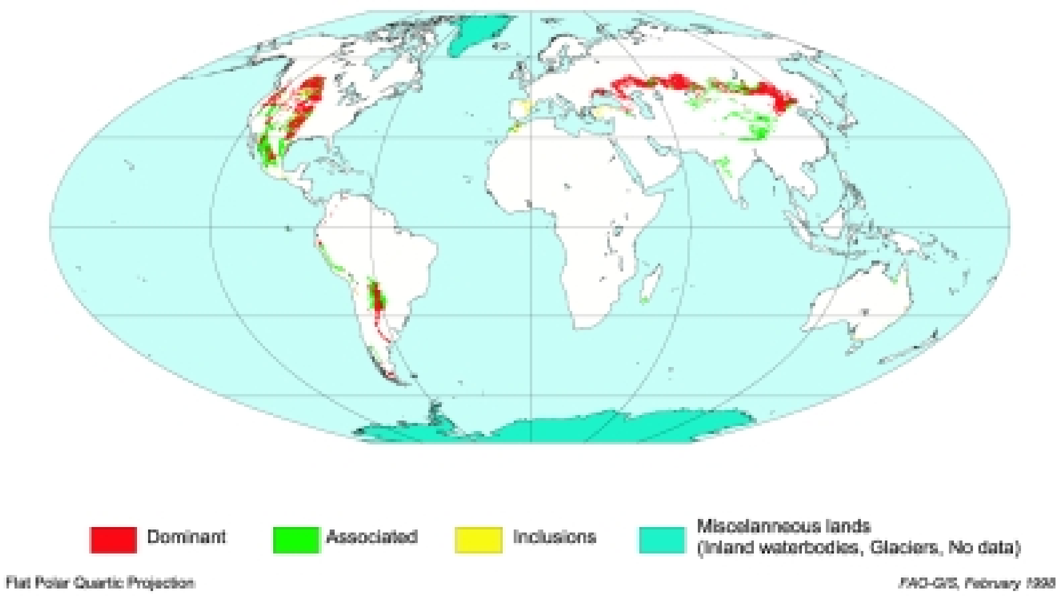
Profile development: mostly AhBC profiles with a brown Ah-horizon of medium depth over a brown to cinnamon cambic or argic B-horizon and with lime and/or gypsum accumulation in or below the B-horizon.

Use: the principal arable land use is the production of small grains and (irrigated) food and vegetable crops. Many Kastanozem areas are used for extensive grazing. Drought and (wind and water) erosion are serious limitations.

Regional distribution of Kastanozems

The total extent of Kastanozems is estimated at about 465 million hectares. Major areas are in the Eurasian short-grass-steppe belt (southern Ukraine, southern Russia, and Mongolia), in the Great Plains of the USA, and in Mexico, southwestern Brazil, and the pampas of Northern Argentina, Uruguay and Paraguay. Figure 1 shows the world-wide occurrence of Kastanozems.

Figure 1
Kastanozems world-wide



Associations with other Reference Soil Groups

Kastanozems on the Northern Hemisphere border on the Chernozem belt in the cooler and less arid north, and on areas with *Calcisols* and *Gypsisols* in the warmer and drier south (where they may also occur adjacent to *Solonchaks* and *Solonetz*). In the warmer and less arid subtropics, Kastanozems are associated with *Phaeozems*.

Genesis of Kastanozems

The climax vegetation of the Kastanozem belt is a short grass vegetation, scanty, poor in species and dominated by ephemera (early ripening species). The aboveground dry biomass amounts to only 0.8-1 tons/hectare, whereas the dry root mass reaches 3-4 tons/hectare. More than 50 percent of all roots are concentrated in the upper 25 cm of the soil and there are few roots that extend down to deeper than 1 metre. The greater part of the grass vegetation dies each summer. This specific vegetation type conditioned Kastanozem formation. Kastanozem surface soils are less deep than those of Chernozems (under tall grasses) and are brown rather than black. The organic matter content of the Ah-horizon of Kastanozems is typically 2 to 4 percent and seldom exceeds 5 percent.

Downward percolation of water in spring leaches solutes from the surface to subsurface and subsoil layers. Lime accumulates at a depth of approximately 1 metre; gypsum accumulation is common in drier regions, mostly at a depth between 150 and 200 cm, and in the driest Kastanozems there may be a layer of salt accumulation deeper than 200 cm below the surface.

A clay illuviation horizon *may* be present as deep as 250-300 cm below the soil surface. The occurrence of argic B-horizons in Kastanozems is still ill understood. They may be fossil, as claimed by some Russian soil scientists, but there are also theories of a more recent formation, through 'normal' translocation of clay, or by destruction of clay or fine earth near the surface and reformation at greater depth.

Climatic gradients in the Kastanozem belt are visible from pedogenic features. In Russia, the darkest surface horizons occur in the north of the Kastanozem belt (bordering on the Chernozems) whereas soils with shallower and lighter coloured horizons are more abundant in the south. The differentiation between horizons is clearer in the north than in the south in line with decreasing length and intensity of soil formation as conditions become more arid.

Characteristics of Kastanozems

Morphological characteristics

The morphology of dark Kastanozems is not very different from that of the southern (drier) Chernozems whereas the light Kastanozems of the south grade into Calcisols. The northern Eurasian Kastanozems have Ah-horizons of some 50 cm thick, dark brown and with a granular or fine blocky structure, grading into cinnamon or pale yellow massive to coarse prismatic B-horizons. In the drier south, the Ah-horizon is only 25 cm thick and colours are lighter throughout the profile.

Argic B-horizons are reported to have "more intense coloration" in Luvic Kastanozems. Accumulations of lime and/or gypsum separate Kastanozems (and Chernozems) from Phaeozems and are particularly prominent in Kastanozems of the southern dry steppes. Krotovinas occur in almost all Kastanozems but are less abundant than in Chernozems.

Hydrological characteristics

Kastanozems have an intermittent water regime. The soils dry out to great depth in the dry season and are often incompletely moistened in wet periods. The low total precipitation sum and low non-capillary porosity of Kastanozems explain why run-off (losses) during and after heavy showers can be considerable. A *'dead dry horizon'* occurs below the limit of wetting; this horizon receives neither percolation water from above nor capillary rise from below and is 'physiologically dead'.

Physical characteristics

The physical properties of Kastanozems are slightly less favourable than of Chernozems but otherwise comparable. The lower humus content of the surface layer, particularly in the lighter Kastanozems, is associated with weaker micro-aggregation, which manifests itself in less total pore volume (40-55 percent), less moisture storage capacity, denser packing of the soil and lower permeability to water.

Chemical characteristics

Kastanozems are chemically rich soils with a cation exchange capacity of 25-30 cmol(+)/kg dry soil, and typically 95 percent base saturation percentage or more. The majority of all adsorbed cations are Ca^{2+} and Mg^{2+}-ions; ESP-values of 4 to 20 have been reported.

The C/N-ratio of the organic soil fraction of the surface horizon is around 10, as in Chernozems. The soil-pH is slightly above 7.0 but may increase to a value around 8.5 at some depth. Accumulations of lime and gypsum are common; the accumulation horizon contains 10 to 20 percent more secondary carbonates than the deeper solum. More easily soluble salts may have accumulated deeper down, deeper in dark Kastanozems than in the lighter soils of the drier steppe. The salt content of the accumulation layer is commonly between 0.05 and 0.1 percent and does not seriously inhibit the growth of crops. In places, salt levels may reach 0.4 percent and more.

Management and use of Kastanozems

Kastanozems are potentially rich soils; periodic lack of soil moisture is the main obstacle to high yields. Irrigation is nearly always necessary for high yields; care must be taken to avoid secondary salinization of the surface soil. Small grains and (irrigated) food and vegetable crops are the principal crops grown. Wind erosion is a problem on Kastanozems, especially on fallow lands.

Extensive grazing is another important land use but the sparsely vegetated grazing lands are inferior to the tall grass steppes on Chernozems and overgrazing is a serious problem.

PHAEOZEMS (PH)

The Reference Soil Group of the Phaeozems accommodates soils of wet steppe (prairie) regions. Phaeozems are much like Chernozems and Kastanozems but are more intensively leached in wet seasons. Consequently, they have dark, humous surface soils that are less rich in bases than surface soils of Chernozems and Kastanozems and Phaeozems have no (signs of) secondary carbonates in the upper metre of soil. Commonly used international names are 'Brunizems' (Argentina, France), 'Degraded Chernozems' (former USSR), 'Parabraunerde-Tsjernozems' (Germany), 'Dusky red prairie soils' (USA) or 'Udolls' and 'Aquolls' in the order of the Mollisols (USDA Soil Taxonomy).

Definition of Phaeozems[#]

Soils having
1. a *mollic*[@] horizon, and
2. a base saturation (in 1 *M* NH_4OAc at pH 7.0) of 50 percent or more and having no secondary carbonates to at least a depth of 100 cm from the soil surface, or to a contrasting layer (*lithic*[@] or *paralithic*[@] contact, *petrocalcic*[@] horizon) between 25 and 100 cm, and
3. no diagnostic horizons other than an *albic*[@], *argic*[@], *cambic*[@] or *vertic*[@] horizon.

Common soil units:
Chernic*, Leptic*, Vertic*, Gleyic*, Vitric*, Andic*, Luvic*, Tephric*, Stagnic*, Abruptic*, Greyic*, Pachic*, Glossic*, Calcaric*, Albic*, Skeletic*, Sodic*, Siltic*, Vermic*, Dystric*, Chromic*, Haplic*.

\# See Annex 1 for key to all Reference Soil Groups
@ Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

SUMMARY DESCRIPTION OF PHAEOZEMS

Connotation: dark soils rich in organic matter; from Gr. *phaios*, dusky, and R. *zemlja*, earth, land.

Parent material: aeolian (loess), glacial till and other unconsolidated, predominantly basic materials.

Environment: flat to undulating land in warm to cool (e.g. tropical highland) regions, humid enough that there is some percolation of the soil in most years but also with periods in which the soil dries out. The natural vegetation is tall grass steppe and/or forest.

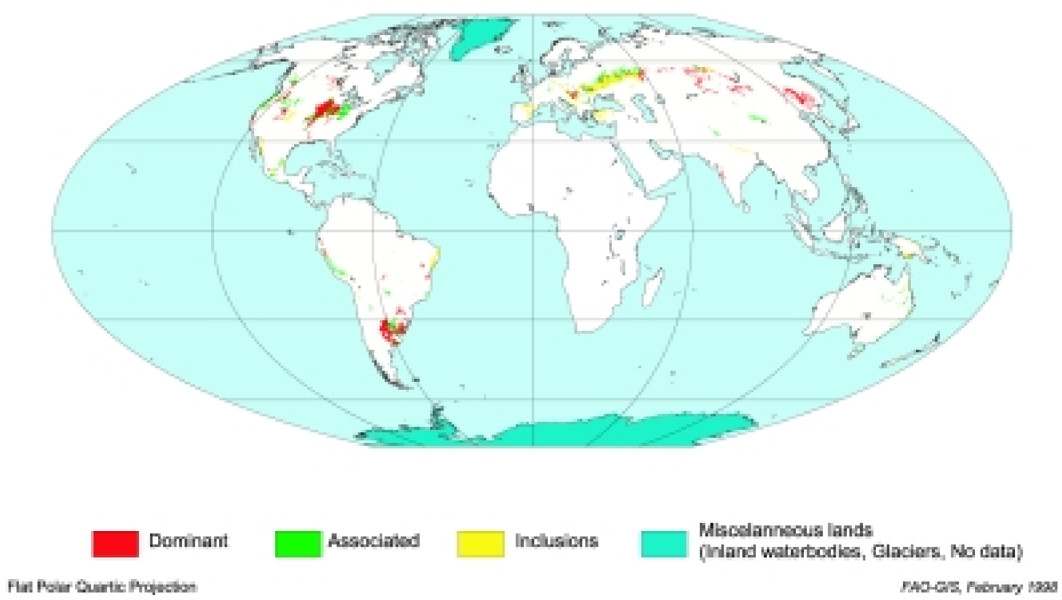
Profile development: mostly AhBC profiles with a mollic surface horizon (thinner and somewhat less dark than in Chernozems) over a cambic or argic subsurface horizon.

Use: Untouched Phaeozems (of which there are few left) carry a grass or forest vegetation. Phaeozems are fertile soils; they are planted to irrigated cereals and pulses or are used for cattle rearing and fattening on improved pastures. Periodic drought and wind and water erosion are the main limitations.

Regional distribution of Phaeozems

Phaeozems cover an estimated 190 million hectares world-wide. Some 70 million hectares of Phaeozems are found in the USA, in the (sub-)humid Central Lowlands and easternmost parts of the Great Plains. Another 50 million hectares of Phaeozems are in the subtropical pampas of Argentina and Uruguay and the third largest distribution area of Phaeozems (18 million hectares) is in northeastern China. Smaller, mostly discontinuous areas are found in Central Europe, notably in the Danube region of Hungary and adjacent parts of Yugoslavia and in elevated areas in the tropics. Figure 1 presents the main Phaeozem areas.

Figure 1
Phaeozems worldwide



Associations with other Reference Soil Groups

Phaeozems occur in steppe, forest-steppe or forest-prairie areas that border on the humid side of the Chernozem belt in the temperate climatic zone and on the humid border of the Kastanozem belt in the subtropics. Phaeozems north of the Eurasian and North American Chernozems may occur together with Albeluvisols; they may even develop uncoated silt and sand grains on structural ped surfaces. South American Phaeozems are associated with Planosols, Solonchaks and Kastanozems.

Genesis of Phaeozems

By and large, Phaeozems occur on fine-textured, basic parent material in more humid environments than Chernozems or Kastanozems. The rates of weathering and leaching of bases are higher in Phaeozems than in Chernozems and Kastanozems. Calcium carbonate is absent from the upper metre of the soil profile but leaching is not so intense that the soils have become depleted of bases and/or plant nutrients. Biomass and faunal activity are high; earthworms and burrowing mammals homogenize the soil. In places, faunal activity is so intense that the mollic A-horizon is thickened and wormholes and krotovinas extend into the C-horizon.

Phaeozem formation appears to be conditioned by an annual precipitation surplus (which infiltrates into the soil). The North American Phaeozem belt extends from Canada, with an annual precipitation sum of only 400 mm and an average temperature of 2 ^{o}C, to Missouri in the south, with 1200 mm rainfall/year and an average temperature of 18 ^{o}C. The precipitation *surplus* over (temperature-dependent) evapotranspiration is about the same from north to south, despite the considerable increase in precipitation sum.

Argic B-horizons do occur in Phaeozems but they are widely regarded as relics from an earlier development towards Luvisols (in eras with a more humid climate).

Characteristics of Phaeozems

Morphological characteristics

Phaeozems have a brown to grey, mollic surface horizon of 30-50 cm over a brown cambic horizon or a yellowish brown C-horizon, or over a brown or reddish brown argic horizon. A-horizons of Phaeozems are thinner than of Chernozems and somewhat less dark. Where the water table is at shallow depth or a perched water table occurs (e.g. on top of an argic horizon), the surface soil may be mottled and/or dark. Luvic soil units, polygenetic or not, represent a more advanced stage of soil formation and tend to have more reddish colours than other Phaeozems.

Hydrological characteristics

Phaeozems with clay accumulation have even better water storage properties than other Phaeozems but may still be short of water in the dry season.

Physical characteristics

Phaeozems are porous, well-aerated soils with moderate to strong, very stable, crumb to blocky structures. Where clay illuviation occurs, the illuviation layer contains commonly 10-20 percent more clay than the overlying horizon.

Chemical characteristics

The organic matter content of the surface layer of Phaeozems is typically around 5 percent; the C/N-ratio of the organic matter is 10-12; pH-values are between 5 and 7 and increase towards the C-horizon. The Cation Exchange Capacity of Phaeozems is 25-30 cmol(+) per kg dry soil or somewhat less; the base saturation percentage lies between 65 and 100 percent, with the higher values in the deeper subsoil.

Management and use of Phaeozems

Phaeozems are porous, fertile soils and make excellent farmland. In the USA and Argentina, Phaeozems are in use for the production of soybean and wheat (and other small grains).

Phaeozems on the High Plains of Texas produce good yields of irrigated cotton. Phaeozems in the temperate climatic belt are planted to wheat, barley and vegetables alongside other crops. Wind and water erosion are serious hazards. Vast areas of Phaeozems are used for cattle rearing and fattening on improved pastures.

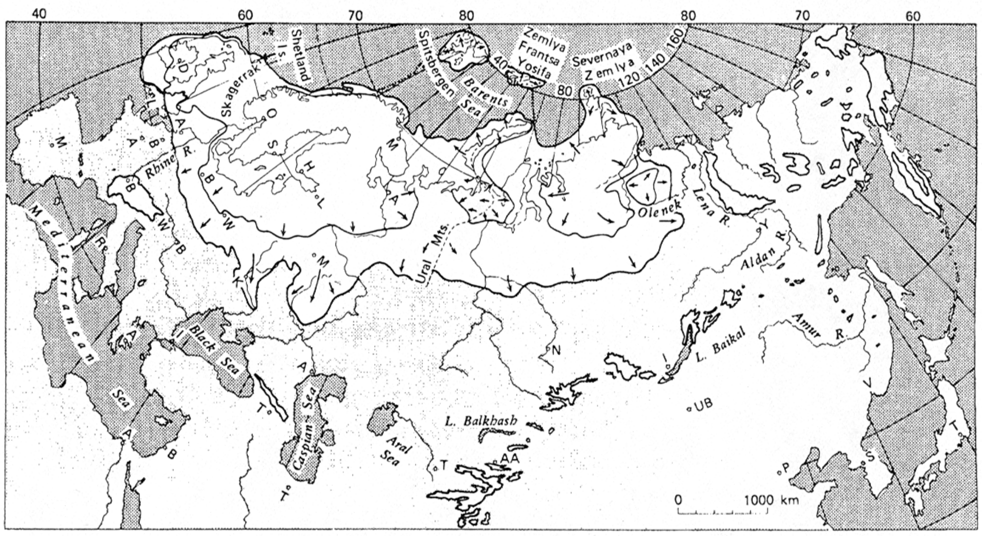
Set #9

MINERAL SOILS CONDITIONED BY A (SUB)HUMID TEMPERATE CLIMATE

Major landforms in (Sub-)Humid Temperate Regions

Most of the Earth's temperate regions were covered with continental ice sheets when the Ice Ages had their maximum expanse. Massive glacial and fluvio-glacial deposits were laid down in these regions when the ice melted. See Figure 1.

Figure 1
Sketch map of Europe and northern Asia, showing the (supposed) maximum extent of glaciated areas in the Pleistocene Ice Ages. Source: Flint, 1971



'Periglacial areas', once adjacent to ice-capped regions, still show evidence of their low temperatures in the past: (older) sediments show characteristic deformation structures and compaction of soil material, incurred in repeated freezing and thawing. Periglacial areas had little vegetation, if any. Strong winds blew sand and silt out of the frozen plains; this material settled again as *'cover sands'* and *sand dunes*, and, at greater distance from the source, as *'loess blankets'*.

Virtually all landforms in temperate regions have in addition to features incurred during past glacial or periglacial periods also some 'typical' characteristics that are associated with the present cool (sub)humid climate:

1. most rivers in the temperate zones have a *regular discharge* regime and traverse vegetated landscapes.
2. most rivers have *meandering channel patterns and low sediment loads*.
3. most rivers tend to *incise rather than to aggrade*.
4. soil *formation and chemical weathering predominate over surface wash*, even in sloping terrain provided that the natural vegetation cover is intact.

Three broad morphotectonic categories can be distinguished in the temperate zones:

1. *'Pleistocene sedimentary lowlands'* with fluvial, glacial, fluvio-glacial, and aeolian deposits;
2. *'Uplifted and dissected sedimentary basins'*, in places with (Mesozoic) limestone, or with sandstone, mudstone, and/or a loess blanket;
3. *'Uplifted and dissected Caledonian and Hercynian Massifs'*, partly consisting of folded sedimentary and low-grade metamorphic rocks and partly of crystalline rocks.

For a discussion of landforms in the third category, the reader is referred to the chapter on the morphology of low-range mountains in eroding uplands.

Major landforms in (peri)glacial and aeolian sedimentary lowlands

Landforms in fluvial and marine environments were discussed in the chapter on 'Landforms in lowlands'; the following paragraphs discuss areas that are underlain by glacial, fluvio-glacial, periglacial or aeolian deposits. Such areas are particularly extensive in the temperate regions of the Northern Hemisphere where continental ice sheets had their greatest expanse during Pleistocene glacial periods. It is generally believed that the Southern Hemisphere had insufficient land at high latitude for extensive ice sheets to develop.

Studies of Pleistocene climate changes suggest that there were at least four advances of continental ice in Eurasia and on the North American continent. Three major advances could be identified in Northwest Europe; they are known as the *'Elster', 'Saale'* and *'Weichsel'* glacial periods; still older ones have been recognised elsewhere, e.g. in northern parts of the Eurasian continent

Glacial advance and retreat produced some typical landforms. The most common ones are:

1. *'till plains'*, e.g. in Denmark and the Drenthe Plateau in The Netherlands;
2. *'moraine complexes'*, e.g. the Salpausselkä in Finland and the Ra moraine in Norway;
3. *'ice-pushed ridges'*, e.g. the 'stuwwallen' in The Netherlands;
4. *'tongue basins'* such as the 'Gelderse Vallei' in The Netherlands, and
5. *'outwash plains'* around terminal moraines or ice-pushed ridges.

The extensive and thick continental ice sheets cooled the air and created a permanent high-pressure area above them. Strong winds blew away from the ice sheets and influenced the climate of regions near the margins of the ice where cold desert conditions prevailed during glacial periods. Arctic tundra vegetation with herbs and (dwarf) shrubs colonised large parts of North America and Northwest Europe. The soil was frozen all-year round (*'permafrost'*) and only during the short summer season would a shallow 'active soil layer' thaw. Even on low-angle slopes, this active layer could slide downhill, producing a *'cryopediment'*.

Repeated thawing and freezing of soil material produced typical *'cryoturbation'* structures and differential heaving of stones, which ultimately resulted in characteristic landscape features such as stone wedges, stony polygons and *'palsas'* (small frozen mounds with peat and/or mineral matter pushed into them). *'Pingos'* i.e. ice lenses that grew year after year into a fractured dome of ice with or without a thin soil cover, can still be traced today because when the ice melted the dome collapsed into a circular depression area. Such *'pingo-ruins'* are a common feature in former periglacial areas, e.g. in the northern Netherlands. Vast tracts of land in periglacial regions became covered with aeolian deposits. Desert pavements, sand plains and dunes were formed at short distances from the ice front, with loess covers farther away. *Note that* dune formation was discussed in the paragraph on residual and aeolian sands; loess deposits were treated in the chapter on landforms in steppes and prairie regions.

Landforms in uplifted sedimentary basins

Most uplifted sedimentary basins in Western Europe and the western USA were formed after the Hercynian orogeny. Their sediments, mostly shallow-water limestone, marls and calcareous sandstone stem from Mesozoic transgressions and regressions. They were never folded but differential subsidence and later uplift have in places resulted in tilting. Elevated flat-topped *'cuesta'* formations are common landscape elements. A cuesta is a tilted, low-angle dipping sequence of resistant sedimentary rocks, which stand out in the landscape as a non-eroded ridge. The ridge itself is the steep escarpment; the gentle slope towards it is known as a *'dipslope'*. Remnants of Tertiary soils on cuesta dipslopes, e.g. the 'clay-with-flint' on Cretaceous chalk ('limons à silex' in France; 'kleefaarde' or 'vuursteeneluvium' in the Netherlands) suggest that these basins formed part of extensive peneplains during the Tertiary. Uplift as a result of orogeny in nearby mountain regions such as the Alps or the Rocky Mountains led to formation of river terraces and incised meanders; the 'Ile de Paris' and the Green River tributary (Colorado, USA) are just two examples.

Many of these basins became partially covered with glacial deposits or were influenced by periglacial processes. Moraines and fluvioglacial deposits are widespread on top of the East-European Platform; large parts of the Paris basin are covered with loess. Only where such covers are absent, e.g. on cuesta slopes that were too high or too steep to collect a thick loess blanket, did soils form in the original parent material.

Podzols are common soils in fluvioglacial and aeolian sands; parabolic dunes of only 2-3 metres height contain fine podzolic catenas that reflect differences in groundwater depth. Luvisols are among the commonest soils in loess blankets in temperate regions; they grade into Chernozems towards the drier end of their zone. Luvisols occur also in (less rigidly sorted) fluvial deposits. Albeluvisols with bleached tongues extending into a clay-enriched subsurface soil are common in clayey glacial till and fine-textured materials of fluvioglacial or glaciolacustrine origin but also in loess. Planosols occur predominantly in sub-humid and semi-arid regions in the Southern Hemisphere. In some instances they formed through degradation of Albeluvisols.

PODZOLS (PZ)

Podzols are soils with an ash-grey subsurface horizon, bleached by organic acids, on top of a dark accumulation horizon with brown or black illuviated humus and/or reddish iron compounds. Podzols occur in humid areas, in particular in the Boreal and Temperate Zones but locally also in the tropics. The name 'Podzol' is used in most national and international soil classification systems; the USDA Soil Taxonomy refers to these soils as 'Spodosols'.

Definition of Podzols#

Soils, having a *spodic*@ horizon starting within 200 cm from the soil surface, underlying an *albic*@, *histic*@, *umbric*@ or *ochric*@ horizon, or an *anthropedogenic*@ horizon less than 50 cm thick.

Common soil units:
Densic*, Carbic*, Rustic*, Histic*, Gelic*, Anthric*, Gleyic*, Umbric*, Placic*, Skeletic*, Stagnic*, Lamellic*, Fragic*, Entic*, Haplic*.

See Annex 1 for key to all Reference Soil Groups
@ Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Podzols

Connotation: soils with a '*spodic*' illuviation horizon under a subsurface horizon that has the appearance of ash; from R. *pod,* under, and *zola,* ash.

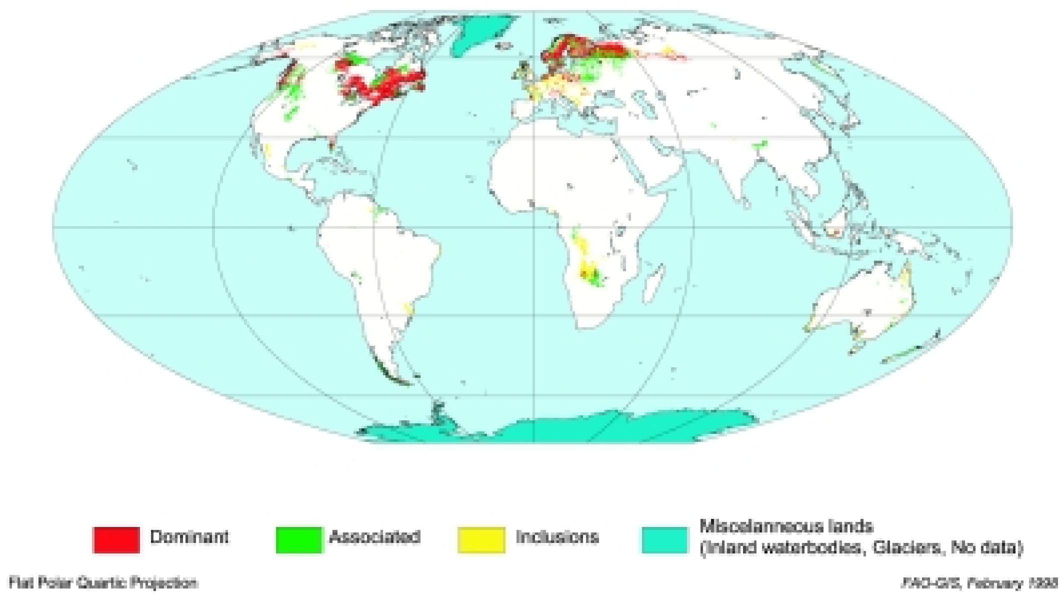
Parent material: unconsolidated weathering materials of siliceous rock, prominent on glacial till, and alluvial and aeolian deposits of quartzitic sands. Podzols in boreal regions occur on almost any rock.

Environment: mainly in temperate and boreal regions of the northern hemisphere, in level to hilly land under heather and/or coniferous forest; in the humid tropics under light forest.

Profile development: mostly O(Ah)EBhsC profiles. Complexes of Al, Fe and organic compounds migrate from the surface soil to the B-horizon with percolating rainwater. The humus complexes precipitate in an illuvial '*spodic*' horizon; the overlying soil remains behind as a strongly leached Ah-horizon and a bleached '*albic*' eluvial horizon. Most boreal Podzols lack an Ah-horizon.

Use: severe acidity, high Al-levels, low chemical fertility and unfavourable physical properties make most Podzols unattractive for arable cropping, unless improved, e.g. by deep-plowing and fertilization. Podzols have some potential for forestry and extensive grazing.

Figure 1
Podzols world-wide



Regional distribution of Podzols

Podzols cover an estimated 485 million hectares world-wide, mainly in temperate and boreal regions on the Northern Hemisphere (see Figure 1). They are extensive in Scandinavia, northwest Russia and Canada. Besides '*zonal*' Podzols, there are smaller occurrences of '*intrazonal*' Podzols, both in the Temperate Zone and in the tropics.

Tropical Podzols occupy less than 10 million hectares, mainly in residual sandstone weathering in perhumid regions and in alluvial quartz sands, e.g. in uplifted coastal areas. The exact distribution of tropical Podzols is not known; important occurrences are found along the Rio Negro and in the Guianas in South America, in the Malesian region (Kalimantan, Sumatra, Irian), and in northern and southern Australia. They seem to be less common in Africa.

Associations with other Reference Soil Groups

Podzols occur together with soils that have evidence of displacement of organic-Fe/Al complexes but not strong enough to qualify as Podzols. *Arenosols, Albeluvisols, Cambisols, Cryosols, Leptosols, Histosols* and *Gleysols* are commonly associated with Podzols but also *Andosols, Anthrosols, Ferralsols* and *Planosols*.

Podzol-Histosol-Gleysol combinations are common in plains with quartzitic sand and a shallow water table in the Temperate Zone. Cryosol-Podzol linkages are found at high latitudes and in places also at high altitude. Tropical Podzols are associated with poor quartzitic *Arenosols*, with *Gleysols* and with *Ferralsols*.

Genesis of Podzols

'*Podzolization*' (the formation of a spodic subsurface horizon) is actually a combination of processes, including

1. '*cheluviation'*, the movement of soluble metal-humus complexes (chelates) out of the surface soil to greater depth, and
2. '*chilluviation*', the subsequent accumulation of Al- and Fe-chelates in a *spodic* horizon. (Soluble organic compounds can move to still deeper horizons.)

Soluble organic substances produced by microbial attack on plant litter move downward with the soil solution and form complexes with Al^{3+}- and Fe^{3+}-ions. The rate of such processes depends strongly on the soil. In poor quartz sands, Podzol morphology is visible after a hundred years of soil formation. Rates are much slower in richer parent materials but the humus fraction of most Podzols appears to have reached equilibrium in 1000-3000 years.

Carboxylic and phenolic groups of dissolved soil organic matter act as 'claws' (Gr. *chela*, hence the term 'chelation') and preferentially 'grab' polyvalent metal ions such as Al^{3+} and Fe^{3+}. This process continues until the binding capacity of the organic matter is saturated. Saturation appears to promote precipitation of the complex. It is likely that transfer of bound metals occurs between highly aggressive but easily decomposable Low Molecular Weight (LMW) acids and less acid but more stable 'humic compounds'.

It appears that uncharged organic matter is also transported by water. This is explained by *'hydrophobic arrangement'*, or *'mycelle behaviour'*: molecules arrange themselves in such a way that their hydrophobic parts are in contact with the interior of 'superstructures', while their charged parts are in contact with water. This causes an apparent solubility of largely hydrophobic units.

In *well-drained soils*, transport of solutes is restricted to the penetration depth of rainfall. Organic matter, with its bound metal ions, precipitates either through saturation (loss of surface charge), or where the waterfront stops. In most cases accumulation of saturated complexes occurs within one metre from the soil surface. Accumulations of different organic matter in irregular bands that reflect the depth of water penetration and the porosity of the matrix material may occur deeper than this illuviation horizon. However, only in extremely poor parent materials, or after extremely long periods of soil formation, will accumulation horizons reach greater depths.

In *hydromorphic Podzols*, dissolved organic matter, with its bound Al, can be transported laterally and over considerable distances. Hydromorphic Podzols in areas with lateral water flow are associated with 'black water' rivers and lakes in boreal, temperate and tropical areas. The limited depth of the phreatic zone usually restricts vertical transport in the soil. Hydromorphic Podzols tend to have slightly deeper eluviation horizons than well-drained relatives in the same climatic zone; their illuvial horizons extend down to greater depths (1-3 metres) and are more vaguely defined. Many hydromorphic Podzols in stratified materials have well-defined humus bands in the subsoil.

The accumulation process is to some extent reversible. If unsaturated organic substances reach the top of an illuviation horizon, the Al,Fe-humus complexes will re-dissolve. Ultimately, an entire spodic horizon moves slowly to a greater depth. Strongly podzolized soils with a very thick *albic* eluviation horizon occur on poor quartz sands, notably in the humid tropics. The illuvial horizon of such soils occurs at a depth of several metres (*'Giant Podzols'*) and may even be absent altogether if the mobile humus is removed by lateral groundwater flow.

Podzolization versus ferralitization

In terms of soil formation, opposite processes take place in Podzols, where Fe- and Al-oxides dissolve and iron and aluminium are leached out, and in Ferralsols where Fe- and Al-oxides remain stable and increase in content through relative accumulation. The main reason for the difference is that organic acids are the principal weathering agents in Podzols whereas carbonic acid plays this role where organic matter decomposition is more rapid, as in Ferralsols.

Strongly leached Ferralsols, although very low in cations and with a soil-pH of 4.0 or less, show no tendency to develop an eluvial horizon. The production of organic acids is too slow and/or their decomposition too fast and the high content of iron oxides would immediately precipitate such complexes. Such soils will podzolize if iron compounds are removed and the clay is decomposed by *ferrolysis* under conditions of periodic water stagnation.

In the wet tropics, soil formation will produce a Ferralsol in most well drained parent materials that are rich in iron and not too siliceous. A Podzol will form in imperfectly drained, coarse-textured and quartz-rich materials, which receive organic matter that decomposes slowly under conditions of oligotrophy.

Characteristics of Podzols

Morphological characteristics

A typical *zonal* Podzol has an ash-grey, strongly leached eluvial horizon under a dark surface horizon with organic matter, and above a brown to very dark brown, *spodic* illuviation horizon. Most Podzols have a surface litter layer (an H-horizon) that is 1 to 5 cm thick, loose and spongy, and grades into an Ah-horizon with partly humified organic matter. In the litter layer in particular, most plant fragments are still recognizable and live roots may be beset with mycorrhizae. The Ah-horizon consists of a dark grey mixture of organic matter and mineral material (mainly quartz). The underlying bleached E-horizon has a single grain structure whereas the structure of the brown to black illuviation horizon varies from loose (rare) through firm, subangular blocky to very hard and massive.

At the drier end of the climatic range for zonal Podzols, the illuviation horizon has commonly a high chroma signifying accumulation of iron oxides (together with aluminium oxides). In more humid regions, the Bhs-horizon is darker and has a higher content of translocated organic matter.

The profile of a typical *intrazonal* tropical Podzol has a surface layer of poorly decomposed ('raw'), acid humus with a high C/N-ratio. The underlying humus-stained A-horizon is poorly developed and rests on top of a light grey to white eluvial E-horizon of sand texture that can be from 20 cm to several metres thick ('Giant Podzols'). The still deeper illuvial horizon is commonly dark brown and irregular in depth. Rarely, one finds mottles or soft concretions of iron and aluminium oxides, and/or slightly more clay in the illuvial horizon than higher in the profile. Brightly coloured B(h)s-horizons with sesquioxides accumulation as occur in the temperate zone (not in 'groundwater Podzols') are uncommon in the tropics where podzolization is largely restricted to iron-poor parent materials under the influence of groundwater.

Mineralogical characteristics

The mineralogy of Podzols is somewhat variable but is nearly always marked by a predominance of quartz. In cool, humid climates where leaching is intense, the parent material may originally have been of intermediate or even basic composition.

Iron and aluminium maxima may occur at different depths in the B-horizon, depending on the genetic history of a particular soil. Podzols in the USA tend to have the maximum iron content above the Al-maximum. Well-developed intrazonal Podzols in Western Europe normally have their maximum Al-contents in the top of the B-horizon, with the Fe- maximum at greater depth.

Weathering processes in the A- and E-horizons of well-developed Podzols in clay-poor materials transform clay to smectite (beidellite), and sometimes kaolinite whereas clay in the B-horizon may be Al-interstratified. Allophane (amorphous Al-silicate) appears to accumulate in B-horizons in rich parent material.

Hydrological characteristics

Hydromorphic Podzols are structurally wet because of climate and/or terrain conditions. Water movement through the soil may be impaired even in upland areas if the soil has a dense illuviation horizon or an indurate layer at some depth. A thin iron-pan can form where there is periodic water stagnation in the soil, either in the B-horizon or below it (e.g. in Densic and Placic Podzols). Even though Podzols are associated with regions that have an annual precipitation surplus, their low water holding capacity may still cause drought stress in dry periods.

Physical characteristics

Most Podzols have a sandy texture and weak aggregation to structural elements; the bleached eluviation horizon contains normally less than 10 percent clay but the clay content could be slightly higher in the underlying illuvial horizon.

Chemical characteristics

The organic matter profile of Podzols shows two areas of concentration, viz. one at the surface and one in the spodic horizon. The C/N-ratio is typically between 20 and 50 in the surface horizon, decreasing to 10 to 15 in the bleached horizon and then increasing again to 15 to 25 in the spodic horizon. Nutrient levels in Podzols are low as a consequence of the high degree of leaching. Plant nutrients are concentrated in the surface horizon(s) where cycling elements are released by decomposing organic debris but phosphates may accumulate in the B-horizon (as Fe or Al-phosphates). The surface horizons are normally acid, with $pH_{(H2O,1:1)}$ values between 3.5 and 4.5. The pH-value of zonal Podzols increases with depth to a maximum of about 5.5 in the deep subsoil, whereas soil-pH in intrazonal Podzols tends to be lowest in the upper B-horizon.

Biological characteristics

In boreal and temperate regions, ‘large’ soil animals such as earthworms are scarce in most Podzols; decomposition of organic matter and surface soil homogenization are slow and are mainly done by fungi, small arthropods and insects. Many Australian Podzols show signs of earthworm activity. The activity of moles and earthworms increases sharply when Podzols are fertilized.

Management and use of Podzols

Zonal Podzols occur in regions with unattractive climatic conditions for most arable land uses. Intrazonal Podzols are more frequently reclaimed for arable uses than zonal Podzols, particularly those in temperate climates. The low nutrient status, low level of available moisture and low soil-pH make Podzols unattractive soils for arable farming. Aluminium toxicity and phosphorus deficiency are common problems. Deep ploughing, to improve the moisture storage capacity of the soil and/or to eliminate a dense illuviation horizon or hardpan, liming and fertilization are the main ameliorative measures taken.

Most zonal Podzols are under forest; intrazonal Podzols in temperate regions are mostly under forest or shrubs (heath). Most tropical Podzols sustain a light forest that recovers only slowly after cutting/burning. By and large, mature Podzols are best used for extensive (sheep) grazing or left idle under their natural (climax) vegetation.

PLANOSOLS (PL)

The Reference Soil Group of the Planosols holds soils with bleached, light-coloured, eluvial surface horizons that show signs of periodic water stagnation and abruptly overly dense, slowly permeable subsoil with significantly more clay than the surface horizon. These soils were formerly regarded as 'pseudogley soils' but are now recognized as 'Planosols' by most soil classification systems. The US Soil Classification coined the name 'Planosols' in 1938; its successor, USDA Soil Taxonomy, includes most of the original Planosols in the Great Soil Groups of the Albaqualfs, Albaquults and Argialbolls.

Definition of Planosols[#]

Soils having

1. an eluvial horizon or loamy sand or coarser materials, the lower boundary of which is marked, within 100 cm from the soil surface, by an *abrupt textural change*[@] associated with *stagnic soil properties*[@] above that boundary, and
2. no *albeluvic tonguing*[@].

Common soil units:

Thionic*, Histic*, Gelic*, Vertic*, Endosalic*, Gleyic*, Plinthic*, Mollic*, Gypsic*, Calcic*, Alic*, Luvic*, Umbric*, Arenic*, Geric*, Calcaric*, Albic*, Ferric*, Alcalic*, Sodic*, Alumic*, Dystric*, Eutric*, Rhodic*, Chromic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups.
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Planosols

Connotation: soils with a degraded, eluvial surface horizon abruptly over dense subsoil, typically in seasonally waterlogged flat lands; from L. *planus*, flat.

Parent material: mostly clayey alluvial and colluvial deposits.

Environment: seasonally or periodically wet, level (plateau) areas, mainly in sub-tropical and temperate, semi-arid and sub-humid regions with light forest or grass vegetation.

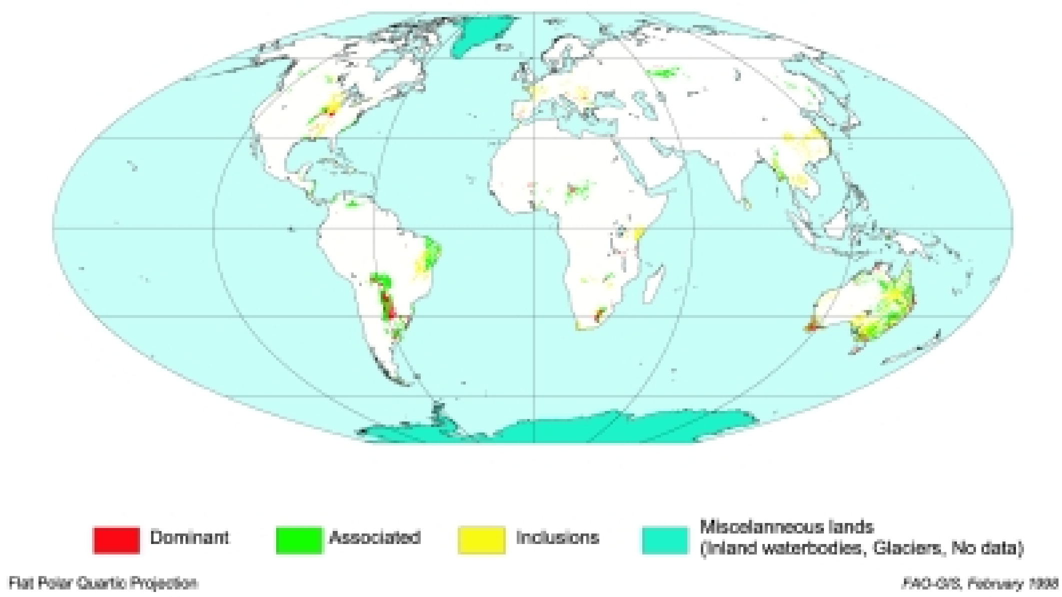
Profile development: AEBC profiles. Destruction and/or removal of clay produced relatively coarse-textured bleached surface soil abruptly overlying finer subsoil. Impeded downward water percolation accounts for *stagnic* soil properties in the bleached horizon.

Use: Planosols are poor soils. In regions with a warm summer season they are mostly under wetland rice. Elsewhere, Planosols are sown to dryland (e.g. fodder) crops or used for extensive grazing. Many Planosol areas are not used for agriculture.

Regional distribution of Planosols

The world's major Planosol areas lie in subtropical and temperate regions with clearly alternating wet and dry seasons, in Latin America (southern Brazil, Paraguay, Argentina), southern and eastern Africa (Sahelian zone, East and southern Africa), the eastern United States, southeast Asia (Bangladesh, Thailand) and in Australia. Their total extent is estimated at some 130 million hectares world-wide. See Figure 1.

Figure 1
Planosols world-wide



Associations with other Reference Soil Groups

Planosols occur predominantly in flat lands but can also be found in the lower stretches of slopes, in a strip intermediate between uplands, e.g. with Acrisols or Luvisols, and lowland (plain or basin) areas, e.g. with Vertisols. Planosols occur also on terraces or somewhat higher up, together with *Acrisols* or other soils with an argic subsurface horizon. In the Ethiopian Highlands, Planosols occur in association with Vertisols in lower parts of the landscape and with Nitisols in higher reaches.

Genesis of Planosols

Planosols have typically a weakly structured *ochric* or *umbric* surface horizon over an *albic* horizon with '*stagnic soil properties'*. The texture of these horizons is markedly coarser than that of deeper soil layers; the transition is sharp and conforms to the requirements of an *'abrupt textural change'*. The finer textured subsurface soil *may* show signs of clay illuviation; it is only slowly permeable to water. Periodic stagnation of water directly above the denser subsurface soil produced typical *stagnic* soil properties in the bleached, eluvial horizon. (And in many soils also to mottling in the upper part of the clayey subsoil). The *'abrupt textural change'* from coarse textured surface soil to finer subsoil can be caused by:

1. *'Geogenetic processes'* such as sedimentation of sandy over clayey layers, creep or sheet wash of lighter textured soil over clayey material, colluvial deposition of sandy over clayey material, or selective erosion whereby the finest fraction is removed from the surface layers, and/or
2. *'Physical pedogenetic processes'* viz. selective eluviation-illuviation of clay in soil material with a low structure stability, and/or
3. *'Chemical pedogenetic processes'* notably a process proposed under the name '*ferrolysis*', an oxidation-reduction sequence driven by chemical energy derived from bacterial decomposition of soil organic matter (Brinkman, 1979).

Ferrolysis is thought to proceed as follows:

In the absence of oxygen (e.g. in water-saturated soils with reducing organic matter), ferric oxides and hydroxides are reduced to Fe^{2+}-compounds which go into solution:

$$CH_2O + 4\ Fe(OH)_3 + 7\ H^+ = 4\ Fe^{2+} + HCO_3^- + 10\ H_2O$$

During this *'reduction phase'*, H^+-ions are consumed and the soil-pH rises. Fe^{2+}-ions replace adsorbed basic cations and aluminium at the exchange complex; the replaced ions are partly leached out (together with some of the Fe^{2+}). Once the soil-pH has risen to about pH 5 to 5.5, Al^{3+}-ions and OH^--ions polymerize to hydroxy-Al-polymers with ring structures. It is surmised that part of the polynuclear Al-polymers are 'trapped' in the interlayer spaces of lattice clays thereby changing the properties of the clay (lower CEC, water content, swell-shrink properties). Remaining polymers are leached out of the soil.

When air re-enters the soil in a subsequent dry period, an *'oxidation phase'* sets in; exchangeable Fe^{2+} is oxidized again to insoluble Fe^{3+}-hydroxide. This produces two H^+-ions for each Fe^{2+}-ion oxidized:

$$4\ Fe^{2+} + O_2 + 10\ H_2O = 4\ Fe(OH)_3 + 8\ H^+$$

The clay turns into hydrogen clay, which converts to aluminium-magnesium clay as adsorbed hydrogen ions are replaced by aluminium and basic cations dissolved from the clay structure. Silica is dissolved from the clay lattices at the same time; it may partly be removed and partly re-precipitate in amorphous form when the eluvial horizon dries out.

During the next wet season, a new cycle starts with another 'reduction phase'.

Note that the abrupt change in clay content and, in some Planosols, in the nature of the clay, can only develop and persist if there is little homogenization of the soil. There are reports of established Planosols that were later transformed to Phaeozems because of intense soil homogenization by termites.

Characteristics of Planosols

Morphological characteristics

A typical horizon sequence of Planosols consists of an ochric or umbric surface horizon over an albic subsurface horizon, directly on top of an argic B-horizon. In very wet locations, the surface horizon may even be a dystric histic horizon whereas surface soils contain very little organic matter in more arid regions. The albic eluviation horizon is invariably greyish and has a sandy or loamy texture and a weak structure of low stability.

The most prominent feature of Planosols is the marked increase in clay content on passing from the degraded eluvial horizon to the deeper soil. The latter may be a slowly permeable argic illuviation horizon, mottled and with coarse angular blocky or prismatic structural elements, or massive and structureless. In most Planosols however, the abrupt change in texture appears to be due to *geo*genetic differentiation or strong weathering in situ in combination with clay destruction in the topsoil.

Mineralogical characteristics

Destruction of clay reduced both the cation exchange capacity of the clay fraction and the soil's moisture retention capacity.

Hydrological characteristics

Planosols are subject to water saturation in wet periods because of stagnation of rain or floodwater. Stagnic soil properties directly above the slowly permeable subsurface layer are telltale signs even in the dry season.

Physical characteristics

The upper soil horizons of Planosols have weakly expressed and unstable structural elements; silty soils in particular become hard as concrete in the dry season and turn to heavy mud when they become waterlogged in the wet season. Sandy surface soil material becomes hard when dry but not cemented. The poor structure stability of the topsoil, the compactness of the subsoil and the abrupt transition from topsoil to subsoil all impair the rooting of crops.

Chemical characteristics

Mature Planosols are chemically strongly degraded. The surface soil has become acidic and lost (much of) its clay; ion exchange properties have deteriorated as a consequence.

Biological characteristics

The natural vegetation of areas with Planosols is light forest and/or herbs or grasses. Where trees grow, it concerns species with extensive, shallow root systems that are capable of withstanding both severe drought and seasonal or occasional water logging. The soil fauna is not very diverse and population densities are low.

Management and use of Planosols

Natural Planosol areas support a sparse grass vegetation, often with scattered shrubs and trees that have shallow root systems and can cope with temporary water logging. Land use on Planosols is normally less intensive than on most other soils under the same climatic conditions. Vast areas of Planosols are used for extensive grazing. Wood production on Planosols is much less than on other soils under the same conditions.

Planosols in the Temperate Zone are mainly in grass or they are planted to arable crops such as wheat and sugar beet. Yields are only modest, even on drained and deeply loosened soils. Root development on natural, unmodified Planosols is severely hindered by oxygen deficiency in wet periods, dense soil at shallow depth and toxic levels of aluminum in the root zone. The low hydraulic conductivity of the dense subsurface soil makes narrow drain spacing inevitable.

Many Planosols in Southeast Asia are planted to a single crop of paddy rice, produced on bunded fields that are inundated in the rainy season. Efforts to produce dryland crops on the same land during the dry season have often met with little success; the soils seemed better suited to a second crop of rice with supplemental irrigation. Fertilizers are needed for good yields. Paddy fields should be allowed to dry out at least once a year to prevent or minimize microelement deficiencies or toxicity associated with prolonged soil reduction. Some Planosols require application of more than just NPK fertilizers and their poor fertility level can prove difficult to correct. Where the temperature permits paddy rice cultivation, this is probably superior to any other kind of land use.

Grasslands with supplemental irrigation in the dry season are a good land use in climates with long dry periods and short infrequent wet spells. Strongly developed Planosols with a very silty or sandy surface soil are perhaps best left untouched.

ALBELUVISOLS (AB)

Albeluvisols are soils that have, within 1 metre from the surface, a clay illuviation horizon with an irregular or broken upper boundary resulting from deep tonguing of bleached soil material into the illuviation horizon. Common international names are Podzoluvisols (FAO), Derno-podzolic or Ortho-podzolic soils (Russia) and several suborders of the Alfisols (USDA Soil Taxonomy).

Definition of Albeluvisols[#]

Soils having, within 100 cm from the surface, an *argic*[@] horizon with an irregular upper boundary resulting from *albeluvic tonguing*[@] into the argic horizon.

Common soil units:
Histic*, Gleyic*, Alic*, Umbric*, Arenic*, Gelic*, Stagnic*, Abruptic*, Ferric*, Fragic*, Siltic*, Alumic*, Endoeutric*, Haplic*.

[#] See Annex 1 for the key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Albeluvisols

Connotation: from L. *albus*, white, and L. *eluere*, to wash out.

Parent material: mostly unconsolidated glacial till, materials of lacustrine or fluvial origin and of aeolian deposits (loess).

Environment: flat to undulating plains under boreal taiga, coniferous forest or mixed forest. The climate is temperate to boreal with cold winters, short and cool summers, and an average annual precipitation sum of 500 to 1000 mm. Precipitation is evenly distributed over the year or, in the continental part of the Albeluvisol belt, has a peak in early summer.

Profile development: mostly AEBtC profiles with a dark, thin ochric surface horizon over an albic subsurface horizon that tongues into an underlying brown clay illuviation horizon. *Stagnic soil properties* are common in boreal Albeluvisols.

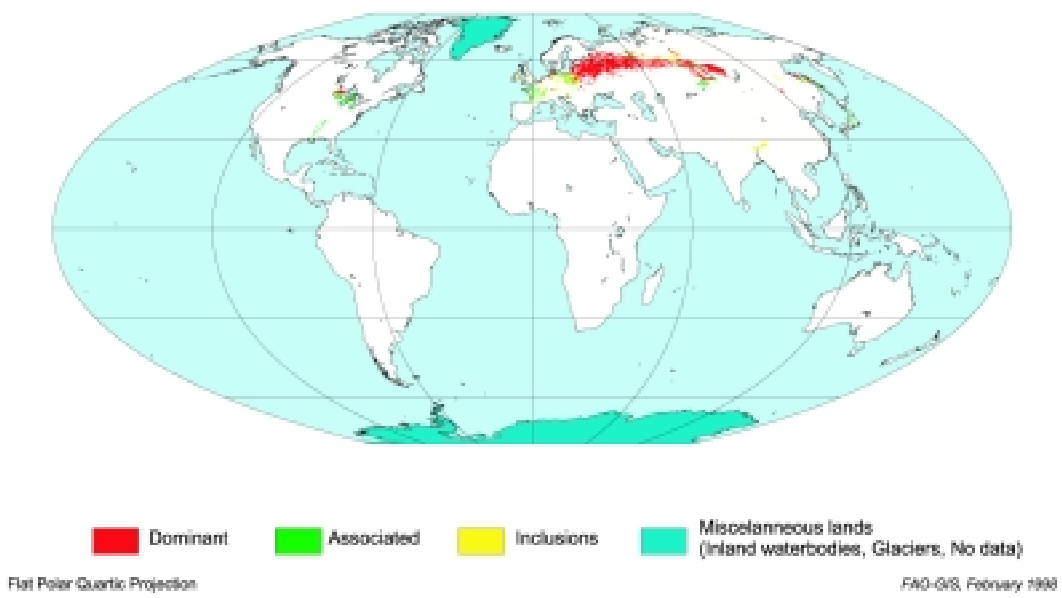
Use: short growing season (frost!), acidity, low nutrient status, tillage and drainage problems are serious limitations of Albeluvisols. Most Albeluvisols are under forest; livestock farming ranks second; arable cropping plays a minor role. In Russia, the share of arable cropping increases towards the south and west of the Albeluvisol belt, especially on relatively nutrient-rich Endoeutric Albeluvisols.

Regional distribution of Albeluvisols

Albeluvisols cover an estimated 320 million hectares in Europe, North Asia and Central Asia, with minor occurrences in North America. Figure 1 shows that Albeluvisols are concentrated in two regions, each having a particular set of climatic conditions:

- cold continental parts of NE Europe, NW Asia and SW Canada, which constitute by far the largest areas of Albeluvisols, and
- loess and cover sand areas and old alluvial areas in moist temperate regions such as France, central Belgium, the south-eastern Netherlands and western Germany.

Figure 1
Albeluvisols world-wide



Associations with other Reference Soil Groups

Albeluvisols have diagnostic horizons and properties in common with *Luvisols* and *Podzols*. They differ from Luvisols by having '*albeluvic tonguing*'. Luvisols may have small penetrations of the overlying horizon into the argic subsurface horizon ('interfingering') but these do not have the dimensions of the tongues in Albeluvisols. Podzols differ from Albeluvisols by their spodic subsurface horizon. Some Albeluvisols have an eluvial horizon with sub-horizons that show characteristics of a spodic horizon. If these features become so pronounced that the sub-horizon qualifies as a spodic horizon, the soil is classified as a Podzol.

Albeluvisols in cold continental areas may border on Podzols to their north. At the interface between both soil groups podzolization of the strongly clay and iron-depleted eluvial horizon is common. Such soils are *'bisequum soils'*, i.e. polygenetic soils with a recent A/E1/Bh solum overlying an older E2/Bt solum.

Albeluvisols in temperate regions occur also together with Podzols, particularly where the latter developed in sandy aeolian deposits. Large parts of the original Albeluvisol belt of Western Europe have now become Luvisols as a result of ploughing and man-induced erosion of the upper decimetres of the soil. The upper 50-80 cm of the original Albeluvisol have changed and its albeluvic tonguing has disappeared after centuries of human intervention. Agricultural activities, notably liming/manuring, have also increased the numbers of burrowing animals such as earthworms and moles and have raised the base saturation of the soils to the extent that they key out as Luvisols. It is common to find Luvisols under agriculture adjacent to Albeluvisols under forest.

Genesis of Albeluvisols

The genesis of Albeluvisols has elements of *'argilluviation'* (i.e. translocation of clay as discussed in the chapter on Luvisols) and elements of present-day or paleo-periglacial (soil) climatic factors. The typical albeluvic tongues, which penetrate into the compacted top of the argic horizon, are the result of periglacial freeze-thaw sequencing during last glacial period.

Albeluvisols occur in regions that had or still have a harsh climate, which explains the little biological activity in their surface horizons. The sudden change in texture from the eluviation horizon to the illuviation horizon hinders internal drainage. Periodic saturation of the surface soil and reduction of iron compounds (enhanced by dissolved organic compounds) cause strong bleaching of the eluvial horizon. The eluvial horizon extends into the underlying argic horizon along root channels and cracks (the characteristic 'tonguing'). This penetration of clay and iron-depleted material into the underlying horizon is distinctly different from the tonguing in (some) Chernozems or Podzols.

Albeluvic tongues have the colour and the coarser texture of the eluvial horizon from which they extend. Tongues must be wider than 5 mm in clayey argic horizons, 10 mm or wider in loamy and silty argic horizons and 15 mm or wider in coarser (silt, loam or sandy loam) argic horizons. The tongues must be deeper than wide and occupy more than 10 % of the volume of the upper 10 cm or the upper quarter (whichever is less) of the argic horizon, both in vertical and horizontal sections.

Albeluvisols are closely related to Albic Luvisols. The main difference is that the eluvial horizon of Albic Luvisols does not extend so prominently into the argic horizon. In most instances the tongues have the same colour as the argic horizon and are less easily detected in the soil profile. (Their lower penetration resistance can be ascertained by piercing them with a knife.)

Periodic saturation with water causes segregation of iron compounds in mottles or concretions of iron (hydr)oxides. Vertical transport of iron compounds may lead to accumulation of iron compounds in a deeper horizon or the iron may be discharged to the subsoil, leaving the soil matrix increasingly depleted. Stagnic properties are present in many Albeluvisols; gleyic properties are much less common.

In the absence of percolation, iron will remain in the soil where it accumulates in 'discrete nodules'. These nodules form upon repeated drying-wetting of the soil with hysteresis between the rates of precipitation of iron compounds in the oxidative phase and of (re)dissolution when the soil is reduced again.

Repeated saturation and leaching of the eluvial horizon cause acidification of the horizon and loss of bases. Ultimately loss of clay and sesquioxides from the eluvial horizon may become so pronounced that only a sandy surface layer remains in which even a micro-Podzol may form. The low organic matter and iron contents of the leached surface soil explain why this layer has low structure stability and low resistance to mechanical stress and why it is normally somewhat compacted. Alternate wetting and drying promotes clay decomposition. In the extreme case, an acid, seasonally wet Planosol may be formed.

At the interface between the eluvial and the illuvial horizons, a *'fragipan'* (from L. *fragere,* to break) can form, commonly overlapping with the argic horizon. A 'fragipan' is a natural, non-cemented subsurface horizon through which roots and percolating water can pass only along preferential paths, e.g. along ped faces. The natural character of the fragipan excludes plough pans and surface traffic pans. The penetration resistance of a fragipan, measured at field capacity, exceeds the reach of most field instruments (50 kN/m).

Characteristics of Albeluvisols

Morphological characteristics

Most untouched Albeluvisols are under forest vegetation. A raw litter layer tops a dark, thin A(h)-horizon over a distinctly bleached eluvial E-horizon that extends into a brown argic illuvial horizon. The top of the argic horizon is normally dense. Clay coatings in the upper half of the argic horizon are invisible to the naked eye. Microscopic examination of thin sections will normally reveal disturbed clay coatings and clay papules within structure elements.

Where the eluvial horizon is not periodically saturated with (ground)water, the eluvial horizon has a brown to yellowish brown colour and contains a fair amount of roots. In the more temperate part of the distribution belt, the eluvial horizon may meet the diagnostic requirements of a cambic horizon. Such a horizon is sometimes referred to as a "biologically active B-horizon" because thin sections show that the entire soil mass is composed of pellets and earthy excrements of soil (micro)fauna. In the colder part of the distribution belt, a thin layer with all features of a spodic horizon may be found in the upper part of the eluvial horizon.

Hydrological characteristics

The configuration of an eluvial horizon on top of an illuvial horizon is, as such, indicative of downward water flow through the soil during at least part of the year. The diagnostic features of an Albeluvisol (viz. iron depletion and tonguing or, alternatively, iron nodules in an eluvial horizon) may or may not be strong enough to meet the specifications of 'stagnic properties' (gley-like features caused by perched water on top of a slowly permeable subsurface horizon).

Mineralogical characteristics

Most Albeluvisols have formed in quartz-rich parent material. The sandier the soil material is, the more pronounced the *albeluvic tonguing*. Many of these parent materials were once calcareous but the upper limit of the calcareous subsoil has since shifted to more than 2 metres below the surface, if it can be found at all. The (clay) mineralogical assembly, which was originally mixed, shows pedogenic differentiation: smectites and interstratified smectites have disappeared from the eluvial horizon and from the albeluvic tongues, where chloritic or degraded chloritic clay minerals have formed. The proportion of smectitic minerals is higher in the argic horizon than in the original parent material.

Physical characteristics

The eluvial horizon is normally sandy. The horizon is typically somewhat compacted; many eluvial horizons have a platy structure. The low organic matter content of the surface soil and its high susceptibility to structure deterioration demand that tillage is done at the proper soil moisture content. The dense argic horizon and/or permafrost may hinder rooting and uptake of water, either directly or indirectly because of its poor internal drainage and inadequate aeration.

Chemical characteristics

The surface horizon of Albeluvisols contains typically between 1 and 10 percent organic carbon; the C/N ratio of the accumulated organic matter is greater than 15. The eluvial subsurface horizon contains rarely more than 1 percent organic C and a similar amount is present in the illuvial horizon. Natural, not cultivated, Albeluvisols are moderately to strongly acid; $pH_{(1M\ KCl)}$ values range from less than 4 to 5.5 or slightly higher. The Cation Exchange Capacity is typically of the order of 10 to 20 cmol(+)/kg, exclusive of the contribution by organic matter. Base saturation varies from a mere 10 percent in Haplic Albeluvisols with much exchangeable aluminium and Al-interlayered clays to values between 60 and 90 percent in cultivated Endoeutric Albeluvisols with little Al-interlayering.

Note that the distinction between Endoeutric and Haplic Albeluvisols is based on the base saturation of the *argic* horizon; the eluvial horizon is always very low in bases.

Biological characteristics

Burrowing animals of the macro- and meso-fauna are scarce in Albeluvisols or absent altogether. Biological activity is accordingly slow and it takes several years before leaves in the litter layer are decomposed to the extent that the original plant tissue is no longer recognisable (i.e. until a *mor* or *moder* type of terrestrial humus has formed). Fungi and actinomycetes account for most of the organic matter decomposition. Another consequence of the low rate of biological activity is that mixing of organic colloids with the mineral soil is slow and the humiferous surface horizon of Albeluvisols is normally only a few centimetres thick. Many Albeluvisols in forest areas in Western Europe, where little or no cattle grazing is practised, have a fragipan overlapping with the argic horizon. In such soils root penetration and water percolation are limited to the albeluvic tongues. If such soils are taken into cultivation, *'bioturbation'* sets in and this can remove the fragipan in a few centuries.

MANAGEMENT/USE OF ALBELUVISOLS

The agricultural suitability of Albeluvisols is limited by their acidity, low nutrient levels, tillage and drainage problems and because the climate dictates a short growing season followed by frost during the long winter. The Albeluvisols of the northern taiga are almost exclusively under forest; small areas are used as pastureland or hay fields. In the southern taiga zone, less than 10 percent of the non-forested area is used for agricultural production. Livestock farming is the main agricultural land use on Albeluvisols (dairy production and cattle rearing); arable cropping (cereals, potatoes, sugar beet, forage maize) plays a minor role.

In Russia, the share of arable farming increases in southern and western directions, especially on Endoeutric Albeluvisols. With careful tillage, liming and application of fertilisers, Albeluvisols can produce 25-30 tons of potatoes per hectare, 2-5 tons of winter wheat or 5-10 tons of dry herbage.

LUVISOLS (LV)

The Reference Soil Group of the Luvisols holds soils whose dominant characteristic is a marked textural differentiation within the soil profile, with the surface horizon being depleted of clay and with accumulation of clay in a subsurface *'argic'* horizon. Luvisols have high activity clays and lack the *abrupt textural change* of Planosols, *albeluvic tonguing* as in Albeluvisols, a *mollic* surface horizon as in steppe soils, and the *alic properties* of Alisols. The name 'Luvisols' is already used in the legend to the FAO Soil Map of the World; local names for these soils include 'Pseudo-podzolic soils' (Russia), 'sols lessivés' (France), 'Parabraunerde' (Germany), 'Grey Brown Podzolic soils' (earlier USA terminology) and 'Alfisols' (USDA Soil Taxonomy).

Definition of Luvisols#

Soils having an *argic*@ horizon with a cation exchange capacity (in 1 M NH_4OAc at pH 7.0) equal to or greater than 24 cmol(+) kg^{-1} clay, *either* starting within 100 cm from the soil surface *or* within 200 cm from the soil surface if the argic horizon is overlain by material that is loamy sand or coarser throughout.

Common soil units
Leptic*, Vertic*, Gleyic*, Vitric*, Andic*, Calcic*, Arenic*, Stagnic*, Abruptic*, Albic*, Profondic*, Lamellic*, Cutanic*, Ferric*, Hyperochric*, Skeletic*, Hyposodic*, Dystric*, Rhodic*, Chromic*, Haplic*.

See Annex 1 for key to all Reference Soil Groups
@ Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Luvisols

Connotation: soils in which clay is washed down from the surface soil to an accumulation horizon at some depth; from L. *luere*, to wash.

Parent material: a wide variety of unconsolidated materials including glacial till, and aeolian, alluvial and colluvial deposits.

Environment: most common in flat or gently sloping land in cool temperate regions and in warm (e.g. Mediterranean) regions with distinct dry and wet seasons.

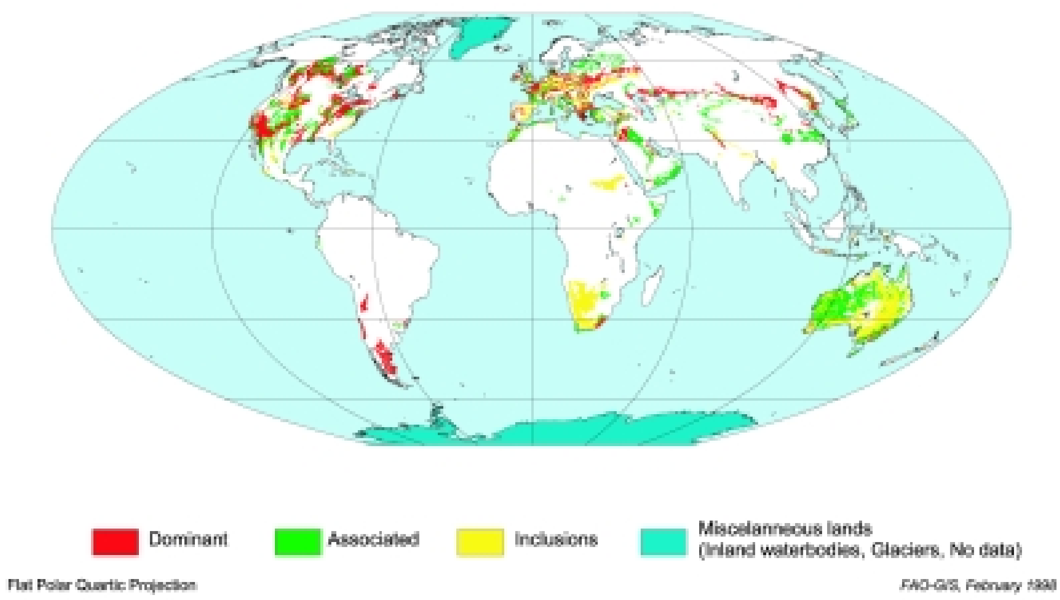
Profile development: ABtC profiles; intergrades to Albeluvisols having an *albic* eluviation horizon above the *argic* subsurface horizon are not rare. The wide range of parent materials and environmental conditions led to a great diversity of soils in this Reference Soil Group.

Use: Luvisols with a good internal drainage are potentially suitable for a wide range of agricultural uses because of their moderate stage of weathering and high base saturation.

Regional distribution of Luvisols

Luvisols extend over 500 to 600 million hectares world-wide, for the greater part in temperate regions such as west/central Russia, the USA and Europe but also in the Mediterranean and in southern Australia. Most Luvisols in subtropical and tropical regions occur on young land surfaces. Figure 1 gives an indication of the major concentrations of Luvisols.

Figure 1
Luvisols world-wide



Associations with other Reference Soil Groups

Luvisols in upland areas are commonly associated with Cambisols; those in lowlands with Gleysols or Solonetz. *Note however that* there are many other Reference Soil Groups with which Luvisols share common properties. For example, Luvisols occurring together with *Vertisols* may have *slickensides* in the argic horizon but not meet the other criteria of a vertic horizon. Luvisols may be associated with *Gypsisols* and *Calcisols* that have an *argic* subsurface horizon; the dominant presence of gypsum and/or calcium carbonate in the argic horizon sets these soils apart from Luvisols. Steppe soils with a dark, base-rich surface horizon that (just) does not qualify as a mollic horizon may be Luvisols and occur in association with *Chernozems* or *Phaeozems*. Luvisols with an umbric surface horizon may well grade into *Umbrisols*. Land use history can affect lateral linkages. Well-known examples are the *Albeluvisols* under forest in the Belgian loess belt that lie adjacent to enriched Luvisols under agriculture. The latter evolved from Albeluvisols but lost albeluvic tonguing (through erosion of the surface soil and increased bioturbation) and acquired a higher base saturation in the argic horizon after years of liming and fertilization.

GENESIS OF LUVISOLS

The dominant characteristic of Luvisols is their *argic* illuviation horizon formed by translocation of clay from the surface soil to the depth of accumulation. The process knows three essential phases:

1. *mobilization* of clay in the surface soil;
2. *transport* of clay to the accumulation horizon;
3. *immobilization* of transported clay.

Normally, clay in soil is not present as individual particles but is clustered to aggregates that consist wholly of clay or of a mixture of clay and other mineral and/or organic soil material. Mass transport of soil material along cracks and pores, common in cracking soils in regions with alternating wet and dry periods, does not necessarily enrich the subsoil horizons with clay.

For an *argic* horizon to form, the (coagulated) clay must disperse in the horizon of eluviation before it is transported to the depth of accumulation by percolating water.

Mobilization of clay

Mobilization of clay can take place if the thickness of the electric 'double layer', i.e. the shell around individual clay particles that is influenced by the charged sides of the clay plates, becomes sufficiently wide. If the double layers increase in width, the bonds between negatively charged sides and positive charges at the edges of clay plates become weaker until individual clay particles are no longer held together in aggregates. The strength of aggregation is influenced by:

- the *ionic strength of the soil solution*,
- the *composition of the ions* adsorbed at the exchange complex, and
- the *specific charge characteristics of the clay* in the soil.

At high electrolyte concentrations of the soil solution, the double layer is compressed so that clay remains flocculated. A decrease in ion concentration, e.g. as a result of dilution by percolating rain water, can result in dispersion of clay and collapse of aggregates. If the exchange complex is dominated by polyvalent ions, the double layer may remain narrow even at low electrolyte concentrations and consequently aggregates remain intact.

Soil-pH may influence both the concentrations of ions in the soil solution and the charge characteristics of the clay. Dispersion of clays is thus, to some extent, a pH-dependent process. At soil-$pH_{(H2O,1:1)}$ values below 5, the aluminium concentration of the soil solution is normally sufficiently high to keep clay flocculated (Al^{3+} is preferentially adsorbed over divalent and monovalent ions in the soil solution). Between pH 5.5 and 7.0, the content of exchangeable aluminium is 'low'. If concentrations of divalent ions are low, clay can disperse. At still higher pH values, divalent bases will normally keep the clay flocculated unless there is a strong dominance of Na^{+}-ions in the soil solution.

Certain organic compounds, especially polyphenols, stimulate mobilization of clay by neutralizing positive charges at the edges of clay minerals. As iron-saturated organic complexes are insoluble, this process might be of little importance in Fe-rich Luvisols (particularly common in the subtropics).

Transport of clay through the soil body

Transport of peptized clay particles requires downward percolation of water through wide (>20 um) pores and voids. Clay translocation is particularly prominent in soils that shrink and crack in the dry season but become wet during occasional downpours.

Note that 'smectite' clays disperse more easily than non-swelling clays; smectite clays are a common constituent of Luvisols.

Precipitation and accumulation of clay

Precipitation of clay particles takes place at some depth in the soil as a result of

1. *flocculation* of clay particles, or
2. (mechanical) *filtration of clay* in suspension by fine capillary pores.

Flocculation can be initiated by an increase in the electrolyte concentration of the soil solution or by an increase of the content of divalent cations (e.g. in a $CaCO_3$-rich subsurface horizon).

Filtration occurs where a clay suspension percolates through relatively dry soil; it forces the clay plates against the faces of peds or against the walls of (bio)pores where skins of strongly *'oriented'* clay (*'cutans'*) are formed. With time, the cutans may wholly or partly disappear through homogenization of the soil by soil fauna, or the cutans may be destroyed mechanically in soils with a high content of swelling clays. This explains why there is often less oriented clay in the argic subsurface horizon than one would expect on the basis of a budget analysis of the clay profile. There could also be more illuviated clay than expected viz. if (part of) the eluviated surface soil is lost through erosion.

Characteristics of Luvisols

Morphological characteristics

Luvisols have typically a brown to dark brown surface horizon over a (greyish) brown to strong brown or red argic subsurface horizon. In subtropical Luvisols in particular, a calcic horizon may be present or pockets of soft powdery lime occur in and below a reddish brown argic horizon. Soil colours are less reddish in Luvisols in cool regions than in warmer climates. In wet environments, the surface soil may become depleted of clay and free iron oxides to the extent that a greyish eluviation horizon forms under a dark but thin A-horizon. Many Luvisols in Western Europe have evolved from Albeluvisols that underwent substantial morphological changes when they were taken into cultivation. Some causes:

- increased erosion led to *truncation* of the Ah-horizon, E-horizon and the larger part of the albeluvic tongues, and
- increased *homogenisation* by soil fauna, notably worms, after a long period of liming and/or fertilization.

Consequently many intergrades exist between Luvisols and Albeluvisols; they reflect the time and intensity of agricultural land use. Examples are Luvisols with a compact argic horizon or with remnants of albeluvic tonguing, or Luvisols with an acid soil reaction in the argic horizon.

Mineralogical characteristics

Luvisols are moderately weathered soils; they contain less Al-, Fe- and Ti-oxides than their tropical counterparts, the Lixisols, and have an SiO_2/Al_2O_3 ratio in excess of 2.0. Luvisols tend to become richer in swelling and shrinking clays towards the dry end of their climatic zone. As a consequence, pressure faces and parallelepiped structure elements become more and more prominent.

Physical characteristics

By and large, Luvisols have favourable physical properties; they have granular or crumb surface soils that are porous and well aerated. The 'available' moisture storage capacity is highest in the argic horizon (15 to 20 volume percent). The argic horizon has a stable blocky structure but surface soils with a high silt content may be sensitive to slaking and erosion.

Most Luvisols are well drained but Luvisols in depression areas with shallow groundwater may develop gleyic soil properties in and below the argic horizon. Stagnic properties are found where a dense illuviation horizon obstructs downward percolation and the surface soil becomes saturated with water for extended periods of time

Chemical characteristics

The chemical properties of Luvisols vary with parent material and pedogenetic history. Surface soils are normally wholly or partly de-calcified and slightly acid in reaction; they contain a few percent organic matter with a C/N ratio of 10 to 15. Subsurface soils tend to have a neutral reaction and may contain some calcium carbonate.

Management and use of Luvisols

With the possible exception of Leptic, Gleyic, Vitric, Albic, Ferric and Dystric soil units, Luvisols are fertile soils and suitable for a wide range of agricultural uses. Luvisols with a high silt content are susceptible to structure deterioration if tilled in wet condition and/or with heavy machinery. Luvisols on steep slopes require erosion control measures.

The eluvial horizons of some Luvisols are depleted to the extent that an unfavourable platy structure formed with *'pseudogley'* (stagnic properties) as a result. This is the reason why truncated Luvisols are in many instances better soils for farming than the original, non-eroded soils.

Luvisols in the Temperate Zone are widely grown to small grains, sugar beet and fodder; in sloping areas they are used for orchards and/or grazing. In the Mediterranean region, where Chromic, Calcic and Vertic Luvisols are common in colluvial deposits of limestone weathering, the lower slopes are commonly sown to wheat and/or sugar beet while (eroded) upper slopes are in use for extensive grazing or planted to tree crops.

UMBRISOLS (UM)

The Reference Soil Group of the Umbrisols contains soils in which organic matter of low base saturation has accumulated at the surface to the extent that it significantly affects the properties and utilization of the soil. Umbrisols are the logical pendant of soils with a mollic horizon (e.g. Chernozems, Kastanozems and Phaeozems). Not previously recognized at such high taxonomic level, these soils are classified in other systems as Umbrepts and Humitropepts (USA Soil Taxonomy), Humic Cambisols and Umbric Regosols (FAO), Sombric Brunisols and Humic Regosols (France) or 'Brown Podzolic soils' (e.g. Indonesia).

Definition of Umbrisols[#]

Soils, having

1. an umbr*ic*[@] horizon, and
2. no diagnostic horizons other than an *anthropedogenic*[@] horizon less than 50 cm thick, an *albic*[@] horizon or a *cambic*[@] horizon.

Common soil units:
Thionic*, Gelic*, Anthric*, Leptic*, Gleyic*, Ferralic*, Arenic*, Stagnic*, Humic*, Albic*, Skeletic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Umbrisols

Connotation: soils with dark topsoil; from L., *umbra*, shade.

Parent material: weathering material of siliceous rock; predominantly in late Pleistocene and Holocene deposits.

Environment: cool and humid climates, e.g. in mountain regions with little or no moisture deficit.

Profile development: AC and A(B)C profiles.

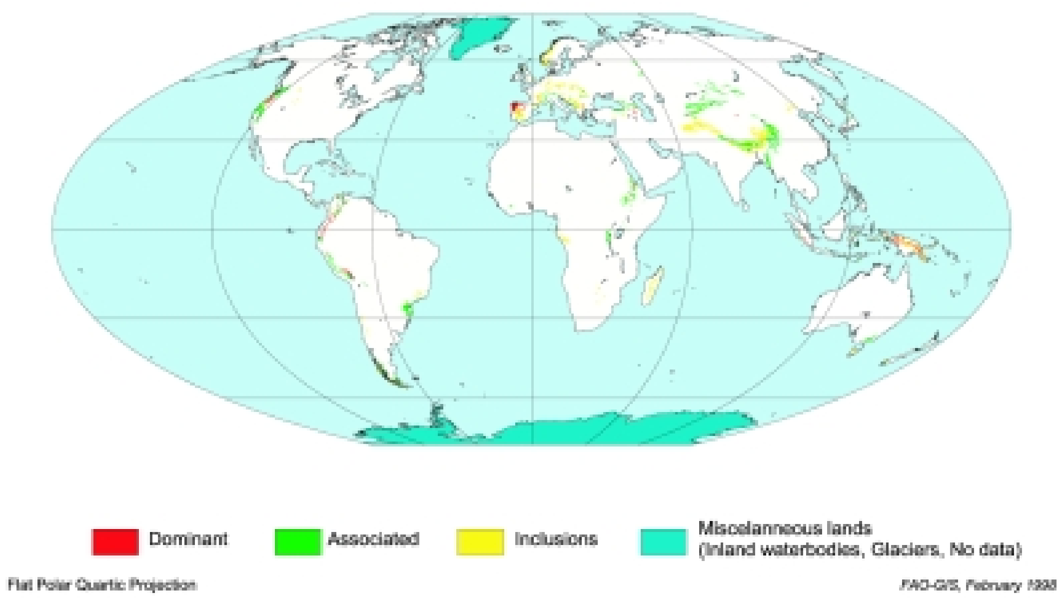
Use: predominantly forestry and extensive grazing. Under adequate management, Umbrisols may be planted to cash crops such as cereals, root crops, tea and coffee.

Regional distribution of Umbrisols

Umbrisols occur in cool, humid regions, mostly mountainous and with little or no soil moisture deficit. They occupy about 100 million hectares throughout the world. In South America, Umbrisols are common in the Andean ranges of Columbia, Ecuador and, to a lesser extent, in

Venezuela, Bolivia and Peru. They occur also in Brazil, e.g. in the Serra do Mar. Umbrisols in North America are largely confined to the north western Pacific seaboard. In Europe, Umbrisols occur along the north western Atlantic seaboard, e.g. in Iceland, on the British Isles and in northwest Portugal and Spain. In Asia, they are found in the mountain ranges east and west of Lake Baikal, and on fringes of the Himalayas, notably in India, Nepal, China and Burma. Umbrisols occur at lower altitudes in Manipur (eastern India), in the Chin Hills (western Burma) and in Sumatra (Barisan range). In Australasia, Umbrisols are found in the mountain ranges of New Guinea and Southeast Australia and in the eastern parts of South Island, New Zealand.

Figure 1
Umbrisols world-wide



Associations with other Reference Soil Groups

Umbrisols are associated with Reference Soil Groups that occur under cool-temperate, moist, free-draining conditions. Linkages vary with the age of the landscape and local conditions.

Umbrisols in cool and/or wet areas are associated with *Regosols* and *Leptosols*, and in places with *Histosols*. In low-lying areas with a fluctuating water table, Umbrisols on lower slopes are found adjacent to *Gleysols* and Histosols (in depressions) and *Cambisols, Podzols*, Regosols and *Leptosols* (at higher elevation).

In places, this general pattern was compromised by human intervention. Where Umbrisols are being cultivated, lime is normally applied in appreciable quantities. This increases the soil's base saturation level, in places to the extent that the umbric horizon comes to resemble a mollic horizon. Ultimately, the Umbrisol changes into a Phaeozem. In other cases, notably in Western Europe, Umbrisols under cultivation have received bulk quantities of organic manure or earthy materials for several centuries. Here, the umbric horizon gradually transformed to a plaggic horizon or a terric horizon. In such areas, a complex mosaic of Umbrisols, Phaeozems and Anthrosols can be found.

Genesis of Umbrisols

Vegetation and climate influence the development of an umbric horizon. In some instances, an umbric horizon may form quite rapidly while concurrent development of an incipient, non-diagnostic, spodic or argic horizon is slow. This explains why umbric horizons are found in young, relatively undeveloped soils that lack any other diagnostic horizon, or have only a weak cambic horizon. Profile development is strongly dependent on deposition of (significant quantities of) organic material with low base saturation at the soil surface.

The organic material that characterises Umbrisols can comprise a variety of humus forms that have been variously described as '*acid* or *oligitrophic mull'*, '*moder*', '*raw humus*' and '*mor*'. It could accumulate because of slow biological turnover of organic matter under conditions of acidity, low temperature, surface wetness, or a combination of these. However, Umbrisols were never cold and/or wet for sufficiently long periods to have developed a diagnostic histic horizon.

Characteristics of Umbrisols

Morphological characteristics

Most Umbrisols have AC or A(B)C profiles. The central concept of Umbrisols is that of deeply drained, medium-textured soils with a dark, acid surface horizon rich in organic matter as the distinguishing feature. Umbrisols may have an *albic* horizon provided that there are no other diagnostic horizons present within 200 cm of the surface. In the absence of an albic horizon a *cambic* horizon may be present as evidence of incipient soil formation. Umbrisols that were modified by Man may have a thickened surface horizon (less than 50 cm thick), which is classified as an *anthropedogenic* horizon.

Hydrological characteristics

Umbrisols do not have particular hydrological characteristics as soil texture and soil depth can vary widely.

Physical and chemical characteristics

Most Umbrisols are moderately deep to deep, medium-textured, permeable and well-drained soils. Gravel, stones and boulders can occur throughout the profile. Base saturation is less than 50 percent in the umbric horizon and normally also deeper down. Umbrisols have good physical properties and a moderate natural fertility level, largely on account of the high organic matter content of the umbric surface horizon. Umbrisols on slopes are susceptible to erosion if exposed to torrential rains.

Management and use of Umbrisols

Many Umbrisols are (still) under a natural or near-natural vegetation cover. Umbrisols above the tree line in the Andean, Himalayan and central Asian mountain ranges, or at lower altitudes in northern and western Europe where the former forest vegetation has been largely cleared, carry a cover of short grasses of low nutritional value. Coniferous forest predominates in Brazil (e.g. *Araucaria spp.*) and in the USA (mainly *Thuja*, *Tsuga* and *Pseudotsuga* species). Umbrisols in tropical mountain areas in south Asia and Australasia are under montane evergreen forest.

The predominance of sloping land and wet and cold climatic conditions restrict land use on most Umbrisols to extensive grazing. Management focuses on introduction of improved grasses and correction of the soil-pH by liming. Many Umbrisols are susceptible to erosion. Planting of perennial crops and bench or contour terracing offer possibilities for permanent agriculture on gentler slopes. Where conditions are suitable, cash crops may be grown, e.g. cereals and root crops in the USA, Europe and South America, or tea and cinchona in south Asia (e.g. Indonesia). Highland coffee on Umbrisols demands high management inputs to meet the stringent nutrient requirements of coffee. In New Zealand, Umbrisols have been transformed into highly productive soils, used for intensive sheep and dairy farming, and production of cash crops.

Set #10

Mineral Soils conditioned by Permafrost

Cryosols

CRYOSOLS[1] (CR)

The Reference Soil Group of the Cryosols comprises mineral soils formed in a permafrost environment. In these soils, water occurs primarily in the form of ice and '*cryogenic processes'* are the dominant soil-forming processes. Cryosols are widely known as 'Permafrost soils'. Other common international names are Gelisols, Cryozems, Cryomorphic soils and Polar Desert soils.

Definition of Cryosols[#]

Soils having one or more *cryic*[@] horizons within 100 cm from the soil surface.

Common soil units:
Turbic*, Glacic*, Histic*, Lithic*, Leptic*, Salic*, Gleyic*, Andic*, Natric*, Mollic*, Gypsic*, Calcic*, Umbric*, Thionic*, Stagnic*, Yermic*, Aridic*, Oxyaquic*, Haplic*.

[#] See Annex 1 for key to all Reference Soil Groups.
[@] Diagnostic horizon, property or material; see Annex 2 for full definition.
* Qualifier for naming soil units; see Annex 3 for full definition.

Summary description of Cryosols

Connotation: frost-affected soils; from Gr. *kraios*, cold, ice.

Parent material: a wide variety of unconsolidated materials, including glacial till and aeolian, alluvial, colluvial and residual materials.

Environment: flat to mountainous areas in Antarctic, Arctic, sub-arctic and boreal regions affected by permafrost, notably in depressions. Cryosols are associated with sparsely to continuously vegetated tundra, open-canopy lichen coniferous forest and closed-canopy coniferous or mixed coniferous and deciduous forest.

Profile development: A(B)C profiles. Cryogenic processes produce cryoturbated horizons, frost heave, thermal cracking, ice segregation and patterned ground microrelief.

Use: Cryosols in their natural state support enough vegetation for extensive grazing of animals. Some areas are used for agriculture, especially in northern Russia and Siberia. Large-scale energy development (oil, gas and hydro), mining and, to a lesser extent, forestry have negative effects on these soils.

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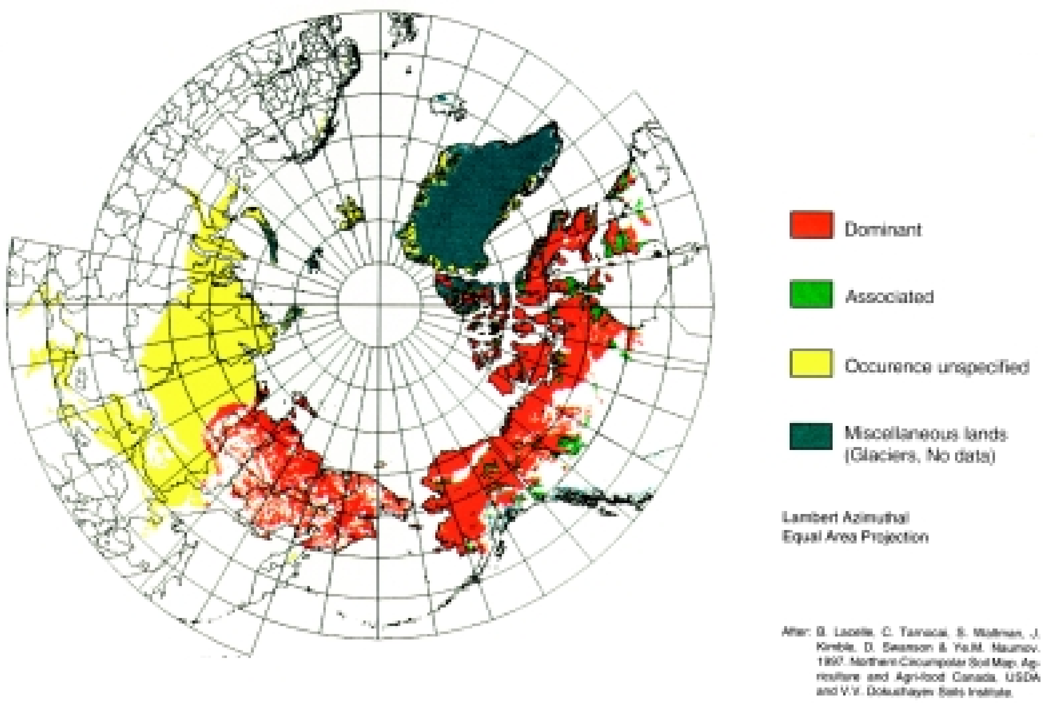
1 This chapter was contributed by C. Tarnocai, Centre for Land and Biological Resources Research, Research Branch, Agriculture Canada, Ottowa, Canada.

Regional distribution of Cryosols

Geographically, Cryosols are circumpolar in both the northern and southern hemispheres. They cover an estimated 18 x 10^6 km^2 or about 13% of the global surface area. Cryosols occur in the permafrost regions of the Arctic, and are also widespread in the sub-arctic zone, discontinuous in the boreal zone and sporadic in more temperate mountainous regions. Major areas with Cryosols are found in Russia (10 x 10^6 km^2), Canada (2.5 x 10^6 km^2), China (1.9 x 10^6 km^2) and Alaska (1.1 x 10^6 km^2) and in parts of Mongolia. Smaller occurrences have been reported from permafrost regions in northern Europe, Greenland and the ice-free areas of Antarctica (Figure 1).

Figure 1
Cryosols in the Northern Hemisphere



Associations with other Reference Soil Groups

Cryosols are often found adjacent to *Histosols* and *Gleysols*. Cryosols on coarse textured-materials and on recent alluvial or aeolian deposits may occur together with *Podzols, Planosols* and/or *Cambisols*. In places, Cryosols are found on north-facing slopes in high elevation areas; south-facing slopes normally have non-permafrost soils.

Genesis of Cryosols

'Cryogenic' processes are the dominant soil-forming processes for Cryosols. Cryogenic processes are driven by soil water as it migrates towards the frozen front along the thermal gradient (from warm to cold) in the system. Cryogenic processes include *'freeze-thaw'* sequences, *'cryo-turbation'*, *'frost heave'*, *'cryogenic sorting'*, *'thermal cracking'*, and *'ice segregation'*.

Freeze-thaw sequences

Repeated cycles of freezing and thawing of water in the soil are responsible for frost heave of coarse materials, cryoturbation (i.e. 'frost churning' of soil material), and mechanical weathering. During 'freeze-back' (the freezing portion of the cycle), freezing fronts move both from the soil surface downward and from the permafrost table upward. As this happens, moisture is removed from the unfrozen soil material between the two fronts (*'frost desiccation'*). Desiccation is responsible for the development of blocky structures in these soils; combination of cryoturbation and desiccation has caused the granular structure of many fine-textured Cryosols. The 'cryostatic pressure' that develops as the freezing fronts merge results in a higher bulk density of the soil.

Cryoturbation (frost churning)

Frost churning mixes the soil matrix and results in irregular or broken soil horizons, involutions, organic intrusions, organic matter occurrences in the subsoil, oriented rock fragments, silt-enriched layers, silt caps and oriented micro-fabrics. Two models have been suggested to explain the cryoturbation process.

- In the *'cryostatic model'*, freezing fronts moving downward from the surface and upward from the permafrost table cause pressure on the unfrozen material between the fronts.
- In the *'convective cell equilibrium model'*, heave-subsidence processes at the top of the active layer move material downward and outward, while heave-subsidence cycles at the bottom move it upward and inward. This results in a slow upward cell-type circulation.

Frost heave

The soil volume expands upon freezing either because of the volume change that takes place when water is converted to ice or because ice build-up in the subsoil causes cracks to form in the soil.

Cryogenic sorting

Separation of coarse soil materials from fine materials takes place at both the macro- and micro-scale. At the macro-scale, cryogenic sorting produces sorted, *'patterned ground'*; at the micro-scale it produces *rounded and banded micro-fabrics*.

Thermal cracking

Frozen materials contract under rapid cooling. The resulting cracks are typically several centimetres wide. They might become filled in with water or sand later to form ice or sand wedges. Since prior thermal cracks are zones of weakness, cracking recurs at the same place.

Ice segregation

This process of ice accumulation in cavities and hollows in the soil mass manifests itself in a variety of phenomena such as *ice lenses*, *vein ice*, *ice crystals* and some types of *ground ice*. The characteristic platy and blocky macro-structures of Cryosols result from vein ice development.

Other soil forming processes

Gleyic properties develop upon prolonged saturation of Cryosols with water (during the thaw period). (Weak) podzolization has been recorded in Haplic Cryosols in coarse-textured materials.

Many Cryosols in cold desert environments are subject to salinization and/or alkalization or show signs of reddening (*'rubefaction'*).

Formation of a cryic horizon

Cryic horizons are perennially frozen soil horizons. They show evidence of cryogenic processes such as the phenomena discussed above and/or characteristic platy, blocky or vesicular macrostructures resulting from vein ice development, and banded microstructures originating from sorting of coarse matrix materials.

If there is little interstitial water, thermal contraction of the frozen (dry) soil materials is weaker than that occurring in soil horizons of higher moisture content.

Formation of Cryosols

The subsoil of Cryosols remains frozen year after year (the *'permafrost layer'*) but the upper portion (the *'active layer'*) thaws in the summer. The maximum thaw depth of the seasonally frozen layer represents the depth of the active layer. Near-surface permafrost is highly dynamic; the active layer increases and decreases in depth in response to environmental and climatic changes. This explains why pedological features that developed when the permafrost table was deeper are sometimes found in the near-surface permafrost.

The active layer in Cryosols normally extends down to 40 to 80 cm below the soil surface; the actual depth depends on the physical environment of the soil and on soil texture, soil moisture regime and thickness of an organic surface layer. Cryosols in the more temperate part of the permafrost zone or at lower elevations have deeper active layers than Cryosols in the High Arctic or at higher elevations. Coarse-textured soils tend to have deeper active layers than adjacent fine-textured soils. Soils with a thick (insulating) organic surface layer have a shallow active layer.

When the temperature drops, freeze-back occurs from the frost table upwards and from the soil surface downwards. The soil material between these freezing fronts comes under *'cryostatic pressure'* and, as a result, unfrozen materials are displaced and soil horizons are contorted and broken. This causes characteristic *'cryogenic structures'* and *'cryoturbated'* soil horizons. Freeze-back also causes coarse fragments to be heaved and sorted, resulting in oriented features in the soil and a micro-topography of 'patterned', sorted and non-sorted, areas at the surface. *Patterned ground* is especially prominent in Arctic areas, with the most common patterned ground types being *circles* (including earth hummocks), *nets, polygons, stripes* and *steps*.

Very low (winter) temperatures let the frozen soil mass shrink and crack, usually in a *polygonal* pattern. Ice builds up in these cracks, and ultimately forms ice wedges. In addition, water moving along the thermal gradient (warm to cold) in the frozen soil builds up to segregated ice (ice lenses, vein ice and pure ice layers) in the soil mass.

Weak leaching and translocation of materials occur in permafrost soils. Leached horizons are common; brownish B-horizons occur as well, in particular in the southern part of the permafrost region. The evidence for translocation of soil material is often partially or completely destroyed by cryoturbation, which mixes the soil materials in the active layer.

CHARACTERISTICS OF CRYOSOLS

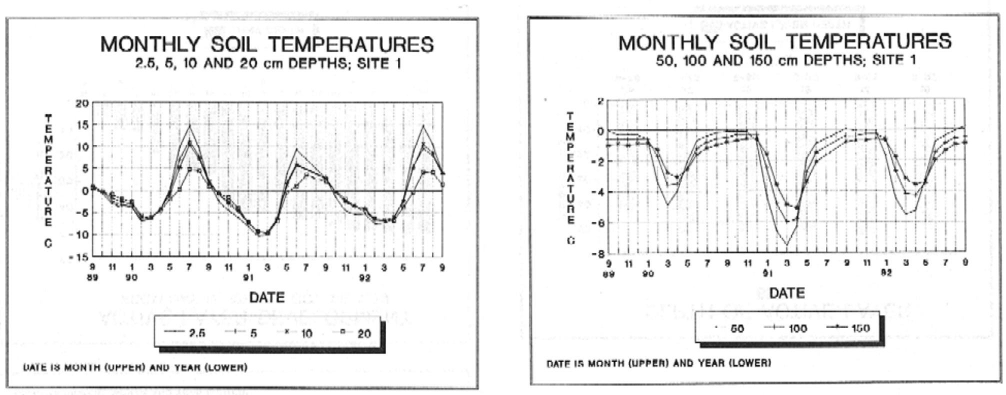
Morphological characteristics

Most Cryosols show evidence of cryoturbation. Cryoturbated soil profiles have irregular or broken soil horizons and many have organic matter incorporated into the lower soil horizons, often concentrated along the top of the permafrost table. Cryoturbation is also accountable for oriented stones in the soil and sorted and non-sorted patterned ground features on the surface.

Freeze-thaw sequences and ice segregation are primarily responsible for the characteristic granular, platy, blocky and *vesicular* (i.e. 'net-shaped') structures of the mineral surface horizon(s). Thixotropy[2] is common in soils with high silt content. A characteristic vesicular structure develops when such soils dry out. The subsurface horizons tend to become massive and densely packed as a consequence of the cryostatic pressure and desiccation that develop during freeze-back, especially in fine-textured soils.

Almost all Cryosols contain accumulations of ice such as ice crystals, ice lenses, ice layers (vein ice), ice wedges or massive ground ice, often to a thickness of several metres. Soil texture is one of the factors controlling ice content in mineral soils. Fine-textured Cryosols generally contain more ice than coarse-textured soils. Although coarse-textured soils have a relatively low ice-content, they are often associated with ice wedges in the form of polygons.

Figure 2
Mean monthly soil temperatures at the 2.5, 5, 10, 20, 50, 100 and 150 cm depths between June 1990 and September 1992. The site is located in the Northwest Territories, Canada, at Lat. 68° 58' 09" N, Long. 133° 32' 54" W. (Tarnocai et al, 1993)



2 It is possible that the more accurate term for this process is *dilatancy*, but thixotropy is the more commonly used term. Dilatancy is defined as: "The increase in volume of a fixed amount of certain materials, as of wet sand, subjected to a deformation that alters the interparticle distances of its constituents from their minimum-value configuration". Alternatively: "Any of various related phenomena, such as increase in viscosity or solidification, resulting from such deformation. Thixotropy, on the other hand, is defined as "The property exhibited by certain gels of liquefying when stirred or shaken and returning to the hardened state upon standing."

The 'active layer' in Cryosols supports biological activity and protects the underlying permafrost. Soil texture, moisture regime, thickness of an organic surface layer, vegetation cover, aspect and latitude are among the factors that control the thickness of the active layer.

Salt crusts are common on soil surfaces on the High Arctic Islands of Canada and in Antarctica. These salt crusts develop during dry periods in the summer because of increased evaporation from the soil surface. Massive salt layers, up to 50 cm thick, have been reported from Antarctica.

Thermal characteristics

Figure 2 presents soil temperatures in a Cryosol north of the arctic tree line in Canada. The unique thermal characteristic that separates Cryosols from all other soils is the presence of a perennially frozen layer, usually deeper than 50 cm. Because of this frozen layer, Cryosols have a steep vertical temperature gradient. If these soils are associated with certain types of patterned ground, the horizontal temperature gradient can also be considerable. For example, Cryosols associated with earth hummocks, may have a summer soil temperature at the centre of the hummock that decreases from 12°C at the surface to 0°C at 50 cm depth. Soil temperatures at comparable depths but measured under the depression between adjacent hummocks, can be 5° to 7°C lower.

Physical characteristics

The physical properties of Cryosol surface soils vary strongly with the season. Thixotropic silt soils are poorly trafficable during the thaw season. The subsoil is always solid with various amounts of ice in the form of segregated ice crystals, ice lenses, ice layers and ice wedges.

Chemical characteristics

The pH of Cryosols varies greatly and depends in part on the composition of the parent material; Cryosols developed in calcareous parent material have a higher soil-pH than soils in non-calcareous material. The similarity of the soil-pH to that of the parent material is also caused, in part, by cryoturbation, which mixes soil materials not only between horizons but also with the parent material.

The nitrogen, potassium and phosphorous contents of Cryosols are generally low. Most plant nutrients are locked into the surface organic matter. Salt accumulation is not uncommon in Cryosols in the dry, cold areas of the Antarctic. Many Cryosols, especially Turbic Cryosols, contain large amounts of organic carbon. Kimble *et al*. (1993) found organic carbon contents of 27.2 to 72.6 kg/m^3 in Turbic Cryosols whereas the carbon contents of non-cryoturbated Cryosols were 3.9 tot 5.4 kg/m^3.

Management and use of Cryosols

Human activities

Natural and man-induced biological activity in Cryosols are confined to the active surface layer that also protects the underlying permafrost. Removal of the peat layer on top of the soil or of the vegetation and/or disturbance of the surface soil often induce rapid environmental change, with possible damage to man-made structures.

Most areas of Cryosols in North America and Eurasia are in the natural state and support sufficient vegetation for grazing animals such as caribou, reindeer and musk oxen. Large herds of caribou still migrate seasonally in the northern part of North America; reindeer herding is an important industry in the vast northern areas, especially in northern Europe. Overgrazing leads rapidly to erosion and other environmental damage.

Human activities, mainly relating to agriculture, oil and gas production and mining, have had a major impact on Cryosols. Severe *'thermokarsting'* has occurred on land cleared for agriculture. Improper management of pipelines and mining can cause oil spills and chemical pollution that affect large areas.

Global warming and Cryosols

It has been predicted that climate warming will cause a significant temperature increase in northern areas. Cryosols contain much organic carbon and act as carbon sinks under the present climate. If the CO_2 content of the atmosphere would double, warming of the circumpolar regions would alter the thermal regime of the soils and increase the depth of the active layer. This would strongly enhance the decomposition of soil organic matter; previously 'fixed' carbon would be released to the atmosphere as carbon dioxide and methane and accelerate global warming even more.

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Online information/Updates

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On-line information/Updates

For additional information/updates the reader may consult the following web sites:

- WRB general information, photographs:
  www.isric.org/WRB.htm

- *WRB detailed information/maps:*
  www.fao.org/waicent/FaoInfo/Agricult/AGL/AGLL/WRB/default.htm

- *WRB documents:*
  www.fao.org/docrep/W8594E/W8594E00.htm

Annexes

Annex 1
Key to Reference Soil Groups

Concepts

The *World Reference Base for Soil Resources* identifies '*diagnostic soil horizons'*, *'diagnostic soil properties'* and *'diagnostic soil materials'*. See Annex 2 for definitions.

- *Diagnostic soil horizons* are internally uniform soil layers delimited by gradual, clear or abrupt upper and lower limits ('boundaries') and characterized by one or more soil characteristics and/or properties occurring over a specific depth.
- *Diagnostic soil properties* are complex soil attributes that involve several soil characteristics and reflect present or past soil forming mechanisms. For example, '*gleyic properties*' refer to soil characteristics such as '*rH*-value =< 19', 'dark blue colour if in contact with potassium ferric cyanide' or 'strong red colour if sprayed with a,a-dipyridyl solution in 10% acetic acid' and to dynamic oxidation-reduction processes of a periodic nature.

Note that 'soil characteristics' are single-value soil attributes that can be observed/measured in the field or laboratory. Soil characteristics include class attributes such as colour, texture or structure class, and discrete attributes expressed in one numerical value such as 'soil depth in cm', 'soil-pH' or 'nominal cation exchange capacity in cmol(+)/kg'.

- *Diagnostic soil materials* are defined as 'materials that reflect the original parent materials, in which pedogenetic processes have not yet been so active that they left a significant mark. They comprise *anthropogenic, calcaric, fluvic, gypsiric, organic, sulfidic* and *tephric* soil material'

The World Reference Base for Soil Resources defines *'Soils'* by the vertical combination of soil horizons, properties and/or characteristics occurring within a defined depth and by the vertical organization ('sequence') of soil horizons.

Key to Reference Soil Groups

Soils having a *histic* or *folic* horizon, and

1. ***either*** 10 cm or more thick from the soil surface to a lithic or paralithic contact;
   or 40 cm or more thick and starting within 30 cm from the soil surface; ***and***
2. having no *andic* or *vitric* horizon starting within 30 cm from the soil surface.

HISTOSOLS (HS)

Other soils having one or more *cryic* horizons within 100 cm from the soil surface.

CRYOSOLS (CR)

Other soils,
either having a *hortic*, *irragric*, *plaggic* or *terric* horizon 50 cm or more thick;
or having an *anthraquic* horizon and an underlying *hydragric* horizon with a combined thickness of 50 cm or more.

ANTHROSOLS (AT)

Other soils,
1. ***either*** limited in depth by *continuous hard rock* within 25 cm from the soil surface; ***or*** having a *mollic* horizon with a thickness between 10 and 25 cm directly overlying material with a calcium carbonate equivalent of more than 40 percent; ***or*** containing less than 10 percent (by weight) fine earth from the soil surface to a depth of 75 cm; ***and***
2. having no diagnostic horizons other than a *mollic*, *ochric*, *umbric* or *yermic* horizon.

LEPTOSOLS (LP)

Other soils,
1. having a *vertic* horizon within 100 cm from the soil surface; ***and***
2. having, after the upper 20 cm have been mixed, 30 percent or more clay in all horizons to a depth of 100 cm or more, or to a contrasting layer (lithic or paralithic contact, *petrocalcic*, *petroduric* or *petrogypsic* horizons, sedimentary discontinuity, etc.) between 50 and 100 cm; ***and***
3. having cracks[1] which open and close periodically.

VERTISOLS (VR)

Other soils,
1. having a thickness of 25 cm or more; ***and***
2. having *fluvic* soil material starting within 50 cm from the soil surface; ***and***
3. having no diagnostic horizons other than a *histic*, *mollic*, *ochric*, *takyric*, *umbric*, *yermic*, *salic* or *sulfuric* horizon.

FLUVISOLS (FL)

Other soils,
1. having a *salic* horizon starting within 50 cm from the soil surface; ***and***
2. having no diagnostic horizons other than a *histic*, *mollic*, *ochric*, *takyric*, *yermic*, *calcic*, *cambic*, *duric*, *gypsic,* or *vertic* horizon.

SOLONCHAKS (SC)

[1] A crack is an open space between gross polyhedrons. Cracks may be filled mainly by granular materials from the soil surface but remain open in the sense that the polyhedrons are separated.

Other soils,

1. having *gleyic* properties within 50 cm from the soil surface; ***and***
2. having no diagnostic horizons other than an *anthraquic*, *histic*, *mollic*, *ochric*, *takyric*, *umbric*, *andic*, *calcic*, *cambic*, *gypsic*, *plinthic*, *salic*, *sulfuric,* or *vitric* horizon within 100 cm from the soil surface.
3. having no *abrupt textural change* within 100 cm from the soil surface.

GLEYSOLS (GL)

Other soils,

1. having a *vitric* or an *andic* horizon starting within 25 cm from the soil surface; ***and***
2. having no diagnostic horizons (unless buried deeper than 50 cm) other than a *histic*, *fulvic*, *melanic*, *mollic*, *umbric*, *ochric*, *duric,* or *cambic* horizon.

ANDOSOLS (AN)

Other soils,
having a *spodic* horizon starting within 200 cm from the soil surface, underlying an *albic*, *histic*, *umbric* or *ochric* horizon, or an *anthropedogenic* horizon less than 50 cm thick.

PODZOLS (PZ)

Other soils,
either having a *petroplinthic* horizon starting within 50 cm from the soil surface;
or having a *plinthic* horizon starting within 50 cm from the soil surface;
or having a *plinthic* horizon starting within 100 cm from the soil surface underlying an *albic* horizon or a horizon with *stagnic* properties.

PLINTHOSOLS (PT)

Other soils,

1. having a *ferralic* horizon at some depth between 25 and 200 cm from the soil surface; ***and***
2. having no *nitic* horizon within 100 cm from the surface; ***and***
3. having no layer, which fulfils the requirements of an *argic* horizon and which has 10 percent or more water-dispersible clay within 30 cm from its upper boundary *unless* the soil material has *geric* properties or contains more than 1.4 percent organic carbon.

FERRALSOLS (FR)

Other soils,
having a *natric* horizon within 100 cm from the soil surface.

SOLONETZ (SN)

Other soils,
1. having an eluvial horizon or materials having loamy sand or coarser textures, the lower boundary of which is marked, within 100 cm from the soil surface, by an *abrupt textural change* associated with *stagnic* properties; ***and***
2. having no *albeluvic tonguing*.

PLANOSOLS (PL)

Other soils,
1. having a *mollic* horizon with a moist chroma of 2 or less if the texture is finer than sandy loam, or less than 3.5 if the texture is sandy loam or coarser, both to a depth of at least 20 cm, or a mollic horizon which has these chromas directly below a plough layer; ***and***
2. having concentrations of *secondary carbonates* starting within 200 cm from the soil surface; ***and***
3. having no *petrocalcic* horizon between 25 and 100 cm from the soil surface; ***and***
4. having no secondary gypsum; ***and***
5. having no uncoated silt and sand grains on structural ped surfaces.

CHERNOZEMS (CH)

Other soils,
1. having a *mollic* horizon with a moist chroma of more than 2 to a depth of at least 20 cm or directly below any plough layer; ***and***
2. having concentrations of *secondary carbonates* within 100 cm from the soil surface; ***and***
3. having no diagnostic horizons other than an *argic*, *calcic*, *cambic*, *gypsic, petrocalcic, petrogypsic* or *vertic* horizon.

KASTANOZEMS (KS)

Other soils,
1. having a *mollic* horizon; ***and***
2. having a base saturation (in 1 *M* NH_4OAc at pH 7.0) of 50 percent or more and having no secondary carbonates to at least a depth of 100 cm from the soil surface, or to a contrasting layer (*lithic* or *paralithic* contact, *petrocalcic* horizon) between 25 and 100 cm; ***and***
3. having no diagnostic horizons other than an *albic*, *argic*, *cambic* or *vertic* horizon.

PHAEOZEMS (PH)

Other soils,
1. having a *gypsic* or *petrogypsic* horizon within 100 cm from the soil surface; ***and***
2. having no diagnostic horizons other than an *ochric* horizon, a *cambic* horizon, an *argic* horizon permeated with gypsum or calcium carbonate, a *vertic* horizon or a *calcic* or *petrocalcic* horizon underlying the *gypsic* or *petrogypsic* horizon.

GYPSISOLS (GY)

Other soils,
having a *duric* or *petroduric* horizon within 100 cm from the soil surface.

DURISOLS (DU)

Other soils,
1. having a *calcic* or *petrocalcic* horizon within 100 cm of the surface; ***and***
2. having no diagnostic horizons other than an *ochric* or *cambic* horizon, an *argic* horizon which is calcareous, a *vertic* horizon or a *gypsic* horizon

CALCISOLS (CL)

Other soils,
Having, within 100 cm from the soil surface, an *argic* horizon with an irregular upper boundary resulting from *albeluvic tonguing* into the argic horizon.

ALBELUVISOLS (AB)

Other soils,
1. having an *argic* horizon, which has a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) of 24 cmol(+) kg^{-1} clay or more, either starting within 100 cm from the soil surface, or within 200 cm from the soil surface if the argic horizon is overlain by loamy sand or coarser textures throughout; ***and***
2. having *alic* properties in most of the layer(s) between 25 and 100 cm from the soil surface; ***and***
3. having no diagnostic horizons other than an *ochric*, *umbric*, *albic*, *andic*, *ferric*, *nitic*, *plinthic* or *vertic* horizon.

ALISOLS (AL)

Other soils,
1. having a *nitic* horizon starting within 100 cm from the soil surface; ***and***
2. having gradual or diffuse horizon boundaries; ***and***
3. having no *ferric*, *plinthic* or *vertic* horizon within 100 cm from the soil surface.

NITISOLS (NT)

Other soils,
1. having an *argic* horizon, which has a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) of less than 24 cmol(+) kg^{-1} clay in some part, either starting within 100 cm from the soil surface, or within 200 cm from the soil surface if the argic horizon is overlain by loamy sand or coarser textures throughout, ***and***
2. having less than 50 percent base saturation (in 1M NH4OAc at pH 7.0) in the major part between 25 and 100 cm.

ACRISOLS (AC)

Other soils,
having an *argic* horizon with a cation exchange capacity (by 1 M NH_4OAc at pH 7.0) equal to or greater than 24 cmol(+) kg^{-1} clay, either starting within 100 cm from the soil surface, or within 200cm from the soil surface if the argic horizon is overlain by loamy sand or coarser textures throughout.

LUVISOLS (LV)

Other soils,
having an *argic* horizon starting within 100cm from the soil surface, or within 200 cm from the soil surface if the argic horizon is overlain by loamy sand or coarser textures throughout.

LIXISOLS (LX)

Other soils,
1. having an *umbric* horizon; ***and***
2. having no diagnostic horizons other than an *anthropedogenic* horizon less than 50 cm thick, an *albic* horizon or a *cambic* horizon.

UMBRISOLS (UM)

Other soils,
either having a *cambic* horizon;
or having a *mollic* horizon;
or having one of the following diagnostic horizons:
- an *andic*, *vertic* or *vitric* horizon starting between 25 and 100 cm below soil surface, *or*
- a *plinthic*, *petroplinthic*, *salic* or *sulfuric* horizon starting between 50 and 100 cm below soil surface, in the absence of loamy sand or coarser materials above these horizons.

CAMBISOLS (CM)

Other soils,
1. having a texture which is loamy sand or coarser ***either*** to a depth of at least 100 cm from the soil surface, ***or*** to a *plinthic*, *petroplinthic* or *salic* horizon between 50 and 100 cm from the soil surface; ***and***
2. having less than 35 percent (by volume) of rock fragments or other coarse fragments within 100 cm from the soil surface; ***and***
3. having no diagnostic horizons other than an *ochric*, *yermic* or *albic* horizon, or a *plinthic*, *petroplinthic* or *salic* horizon below 50 cm from the soil surface.

ARENOSOLS (AR)

Other soils.

REGOSOLS (RG)

Annex 2
Diagnostic horizons, properties and materials

Diagnostic Horizons

Albic horizon

An *albic* horizon must:

1. have a Munsell colour, dry, with a value of 7 or 8 and a chroma of 3 or less; or a value of 5 or 6 and chroma of 2 or less; and
2. have a Munsell colour, moist, with a value of 6, 7 or 8 and a chroma of 4 or less; or a value of 5 and a chroma of 3 or less; or a value of 4 and chroma of 2 or less[1] (a chroma of 3 is permitted if parent materials have a hue of 5 YR or redder and the chroma is due to the colour of uncoated silt or sand grains); and
3. have a thickness of 1 cm or more.

Andic horizon

An *andic* horizon must have all of the following:

1. a bulk density at field capacity (no prior drying) of less than 0.9 kg dm^{-3}; and
2. 10 percent or more clay and an (Al_{ox} + ½Fe_{ox}) value[2] in the fine earth fraction of 2 percent or more; and
3. 70 percent or more phosphate retention; and
4. less than 10 percent volcanic glass in the fine earth fraction; and
5. a thickness of 30 cm or more.

Anthraquic horizon (see Anthropedogenic horizons)

Anthropedogenic horizons

Note that the precise diagnostic criteria for anthropedogenic horizons are still under review. According to present knowledge they are described as follows.

A *terric* horizon (from L. *terra*, earth) results from addition of earthy manure, compost or mud over a long period of time. The terric horizon has a non-uniform textural differentiation

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[1] Colour requirements differ slightly from those defined by FAO (1988) and Soil Survey Staff (1996). Modifications were made to accommodate albic horizons, which show a considerable shift in chroma upon moistening.

[2] Al_{ox} and Fe_{ox} are acid oxalate extractable aluminium and iron.

with depth. The source material and/or underlying substrates influence the colour of the terric horizon. Base saturation (in 1 *M* NH_4OAc at pH 7.0) is more than 50 percent.

An *irragric* horizon (from L. *irrigare*, to irrigate, and *agricolare*, to cultivate) is a light coloured (Munsell colour value and chroma, moist, both greater than 3), uniformly structured surface layer, developed through long-continued irrigation with sediment-rich water. Clay and carbonates are evenly distributed and the irragric horizon has more clay, particularly fine clay, than the underlying soil material. The weighted average organic carbon content exceeds 0.5 percent, decreasing with depth but remaining at least 0.3 percent at the lower limit of the irragric horizon.

A *plaggic* horizon (from Dutch *plag*, sod) has a uniform texture, usually sand or loamy sand. The weighted average organic carbon content exceeds 0.6 percent. The base saturation (in 1 *M* NH_4OAc at pH 7.0) is less than 50 percent. The content of P_2O_5 extractable in 1 percent citric acid is more than 0.25 percent within 20 cm of the surface (frequently more than 1 percent).

A *hortic* horizon (from L. *hortus*, garden) results from deep cultivation, intensive fertilisation and/or long-continued application of organic wastes. It is a dark coloured horizon with Munsell colour value and chroma (moist) of 3 or less. The hortic horizon has a weighted average organic carbon content of 1 percent or more, and more than 100 mg kg^{-1} (0.5 *M* NaHCO[3] extractable) P_2O_5 in the fine earth fraction of the upper 25 cm layer. Base saturation (in 1 *M* NH_4OAc at pH 7.0) is 50 percent or more.

An *anthraquic* horizon (from Gr. a*nthropos*, human, and L. *aqua*, water) represents a *puddled layer or a plough pan*. Characteristically, plough pans have a platy structure; they are compacted and slowly permeable to water. Yellowish-brown, brown or reddish-brown rust mottles occur along cracks and root holes. The bulk density of the plough pan is at least 20 percent greater than that of the puddled layer, whereas its porosity is 10 to 30 percent less than that of the puddled layer. Non-capillary porosity is 2 to 5 percent.

A *hydragric* horizon (from Gr. *hydros*, water, and L. *agricolare*, to cultivate) is a subsurface horizon with characteristics associated with wet cultivation:

- Iron-manganese accumulation or coatings of illuvial Fe and Mn; or Twice as much dithionite-citrate extractable iron than in the surface horizon(s), or more, or 4 times as much dithionite-citrate extractable manganese or more; or
- Redoximorphic features associated with wet cultivation; and
- Thickness of more than 10 cm.

Argic horizon

An *argic* horizon must:

1. have a texture of sandy loam or finer and at least 8 percent clay in the fine earth fraction; and
2. have more 'total' clay than an overlying coarser textured horizon (exclusive of differences, which result from a lithological discontinuity), such that:
    - if the overlying horizon has less than 15 percent 'total' clay in the fine earth fraction, the argic horizon must contain at least 3 percent more clay; or

[3] Known as the Olsen routine method (Olsen *et al*., 1954).

   - if the overlying horizon has between15 and 40 percent 'total' clay in the fine earth fraction, the ratio of 'total' clay in the argic horizon to that in the overlying horizon must be 1.2 or more; or
   - if the overlying horizon has 40 percent or more 'total' clay in the fine earth fraction, the argic horizon must contain at least 8 percent more clay; and
3. have a markedly increased clay content relative to the overlying horizon, within a vertical distance of 30 cm if the argic horizon is formed by clay illuviation or within a vertical distance of 15 cm in any other case; and
4. have no autochthonous rock structure in at least half the volume of the horizon; and
5. have a thickness of at least one tenth of the accumulated thickness of all overlying horizons with a minimum of 7.5 cm. If the argic horizon is entirely composed of lamellae, these must have a combined thickness of at least 15 cm. The coarser textured horizon overlying the argic horizon must be at least 18 cm thick, or 5 cm if the textural transition to the argic horizon is abrupt (see *under abrupt textural change*).

Calcic horizon

A *calcic* horizon must:

1. show evidence of secondary carbonates accumulation, and
2. have an equivalent calcium carbonate content of 15 percent or more in the fine earth fraction (*hypercalcic* horizons contain more than 50 percent calcium carbonate equivalent in the fine earth fraction); and
3. have a thickness of 15 cm or more.

Cambic horizon

A *cambic* horizon must:

1. have a texture of sandy loam or finer; and
2. have soil structure, which is at least moderately developed whereas autochthonous rock structure is absent from at least half the volume of the horizon; and
3. show evidence of alteration in one or more of the following forms:
   - stronger chroma, redder hue, or more clay than the underlying horizon;
   - evidence of removal of carbonates.

   Note: if carbonates are absent in the parent material and in the dust that falls on the soil, presence of soil structure and absence of rock structure are enough evidence of alteration; and
4. lack the brittle consistence (moist) that is typical of a *fragic* horizon; and
5. have
   - a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) greater than 16 cmol(+) kg^{-1} clay; or
   - an effective cation exchange capacity (sum of exchangeable bases plus exchangeable acidity in 1 *M* KCl) greater than 12 cmol(+) kg^{-1} clay; or
   - 10 percent or more weatherable minerals in the 50-200 mm fraction[4]; or
   - 10 percent or more water dispersible clay; and
6. have a thickness of 15 cm or more, with the base of the horizon at least 25 cm below the soil surface.

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[4] Instead of analysing the weatherable mineral content, this requirement may be replaced by the analysis of the total reserve in bases (TRB = exchangeable plus mineral Ca, Mg, K and Na). A TRB of 25 $cmol_c$ kg^{-1} soil correlates well with an amount of 10 percent weatherable minerals in the 50-200 ?m fraction.

Chernic horizon

A *chernic* horizon must:

1. have granular or fine subangular blocky soil structure; and
2. have, in the upper 15 cm of the horizon, or immediately below any plough layer, in both broken and crushed samples with a Munsell chroma of less than 2.0 when moist, a value darker than 2.0 when moist and 3.0 when dry. The colour value, moist, must be 3 or less if there is more than 40 percent finely divided lime, or if the texture of the horizon is loamy sand or coarser. The colour value must be at least one unit darker than that of the C-horizon[5] (both moist and dry), unless the soil is derived from dark coloured parent material. If a C-horizon is not present, comparison should be made with the horizon immediately underlying the surface horizon; and
3. have 50 percent or more (by volume) of the horizon consisting of wormholes, worm casts, and/or filled animal burrows; and
4. have at least 1.5 percent organic carbon (2.5 percent organic matter) throughout after mixing. The organic carbon content must be at least 6 percent if the colour requirements are waived because of presence of finely divided lime, or at least 1.5 percent more than that of the C-horizon if colour requirements are waived because of dark coloured parent materials; and
5. have 80 percent base saturation or more (in 1 *M* NH_4OAc at pH 7.0); and
6. have a thickness of at least 35 cm. *Note that* the thickness measurement of a chernic horizon includes transitional horizons in which the characteristics of the surface horizon are dominant - for example, AB, AE or AC.

Cryic horizon

A *cryic* horizon must:

1. have a (soil) temperature at or below 0°C for two or more years in succession; and
2. have - in the *presence* of interstitial soil water, evidence of cryoturbation, frost heave, cryogenic sorting, thermal cracking, or ice segregation;
   or have - in the *absence* of interstitial soil water, evidence of thermal contraction of frozen soil material; and
3. have platy or blocky macro-structure resulting from vein ice development, and orbicular, conglomeratic and banded micro-structure resulting from sorting of coarse soil material.

Duric horizon

A *duric* horizon must:

1. have 10 percent or more (by volume) of durinodes with the following properties:
   - durinodes do not break down in concentrated hydrochloric acid (HCl), but break down in hot concentrated potassium hydroxide (KOH) after treatment with HCl; and
   - durinodes are firm or very firm, and brittle when wet, both before and after treatment with acid; and
   - durinodes have a diameter of 1 cm or more; and
2. have a thickness of 10 cm or more.

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[5] Reference is made here to the master horizon nomenclature as used in FAO's Guidelines for Soil Profile Description (1990); see Appendix 1).

Ferralic horizon

A *ferralic* horizon must:

1. have sandy loam or finer particle size and have less than 90 percent (by weight) gravel, stones or petroplinthic (iron-manganese) concretions; and
2. have a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) of 16 cmol(+) kg^{-1} clay or less and have an effective cation exchange capacity (sum of exchangeable bases plus exchangeable acidity in 1 *M* KCl) of less than 12 cmol(+) kg^{-1} clay; and
3. have less than 10 percent water-dispersible clay, unless the soil material has geric properties or contains more than 1.4 percent organic carbon; and
4. have less than 10 percent weatherable minerals in the 50-200 mm fraction; and
5. have no characteristics diagnostic for the *andic* horizon; and
6. have a thickness of at least 30 cm.

Ferric horizon

A *ferric* horizon must:

1. have coarse mottles with hues redder than 7.5YR and/or chromas in excess of 5 that cover more than 15 percent of the exposed surface area; or
2. have discrete nodules, up to 2 cm in diameter, whose exteriors are enriched and weakly cemented or indurated with iron and have redder hue or stronger chroma than the interior; and

c. have a thickness of at least 15 cm.

Folic horizon

A *folic* horizon must:

1. have more than 20 percent (by weight) organic carbon (35 percent organic matter); and
2. not be saturated with water for more than one month in most years; and
3. have a thickness greater than 10 cm; if a folic horizon is less than 20 cm thick, the upper 20 cm of the soil (after mixing) must contain 20 percent or more organic carbon.

Fragic horizon

A *fragic* horizon must:

1. have greater (bulk) density than overlying horizons; and
2. have less than 0.5 percent organic carbon; and
3. have a penetration resistance at field capacity in excess of 50 kN m^{-2}; and
4. display slaking or fracturing of an air-dry clod within 10 minutes after being placed in water; and
5. have no cementation brought about by repeated wetting and drying; and
6. have a thickness of at least 25 cm.

Fulvic horizon

A *fulvic* horizon must:

1. have properties characteristic for andic horizons throughout the fulvic horizon; and
2. have a Munsell colour value (moist) and chroma of 2 or less; and
3. have a melanic index[6] of more than 1.7 throughout; and
4. have a weighted average organic carbon content of 6 percent or more and 4 percent organic carbon or more in all parts of the fulvic horizon; and
5. have a cumulative thickness of at least 30 cm with less than 10 cm "non-fulvic" material in between.

Gypsic horizon

A *gypsic* horizon must:

1. contain 15 percent or more gypsum. *Note that* the horizon qualifies as a *hypergypsic* horizon (from Gr. *hyper*, superseding, and L. *gypsum*) if it contains 60 percent or more gypsum. The percentage gypsum is calculated as the product of gypsum content, expressed in cmol(+) kg^{-1} soil, and the equivalent weight of gypsum expressed as a percentage (i.e. 86); and
2. have a thickness of at least 15 cm (also for hypergypsic horizons).

Histic horizon

A *histic* horizon must:

1. have 18 percent (by weight) organic carbon (30 percent organic matter) or more if the mineral fraction comprises 60 percent or more clay; or
   have 12 percent (by weight) organic carbon (20 percent organic matter) or more if the mineral fraction has no clay; or
   have a proportional lower limit of organic carbon content, between 12 and 18 percent, if the clay content of the mineral fraction is between 0 and 60 percent. In materials characteristic for *andic* horizons, the organic carbon content must be more than 20 percent (35 percent organic matter); and
2. be saturated with water for at least one month in most years (unless artificially drained); and
3. have a thickness of 10 cm or more. A histic horizon less than 20 cm thick must have 12 percent or more organic carbon after mixing down to a depth of 20 cm.

Hydragric horizon (see anthropedogenic horizons)

Hortic horizon (see anthropedogenic horizons)

Irragric horizon (see anthropedogenic horizons)

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6 See Honna et al. (1988).

Melanic horizon

A *melanic* horizon must:

1. have the properties and characteristic of *andic* horizons; and
2. have Munsell colour value (moist) and chroma of 2 or less; and
3. have a melanic index[7] of 1.70 or less throughout; and
4. have a weighted average organic carbon content of 6 percent or more and 4 percent or more organic carbon in all parts; and
5. have a cumulative thickness of at least 30 cm with less than 10 cm "non-melanic" material in between.

Mollic horizon

A *mollic* horizon must:

1. have
   - structural units with a diameter of 30cm or less or secondary structure with a diameter of 30cm or less (when dry); and/or
   - a moderately hard or softer rupture resistance class (when dry); and
2. have a Munsell chroma of less than 3.5 (moist), a value darker than 3.5 (moist) and 5.5 (dry) in both broken and crushed samples. If there is more than 40 percent finely divided lime, the colour value (moist) must be 5 or less. The colour value must be at least one unit darker than that of the C-horizon (both moist and dry), unless the soil is derived from dark coloured parent material. If a C-horizon is not present, comparison should be made with the horizon immediately underlying the surface horizon; and
3. have 0.6 percent organic carbon (1 percent organic matter) or more throughout the (mixed) horizon. The organic carbon content is at least 2.5 percent if the colour requirements are waived because of finely divided lime, or 0.6 percent more than that of the C-horizon if the colour requirements are waived because of dark coloured parent materials; and
4. have a weighted average base saturation (in 1 *M* NH_4OAc at pH 7.0) of 50 percent or more throughout the depth of the horizon; and
5. have thickness specifications as follows:
   - 10 cm or more if directly on hard rock, a *petrocalcic*, *petroduric* or *petrogypsic* horizon, or overlying a cryic horizon or material containing more than 40 percent CaCO3; or
   - 20 cm or more and more than one-third of the thickness of the solum if the solum is less than 75 cm thick; or
   - 25 cm or more if the solum is more than 75 cm thick.

Note that the thickness specifications of a mollic horizon include transitional horizons in which the characteristics of the surface horizon are dominant - for example, AB, AE or AC. The requirements for a mollic horizon must be met after the first 20 cm are mixed, as in ploughing.

[7] See Honna et al. (1988).

Natric horizon

A *natric* horizon must:

1. have sandy loam or finer texture and at least 8 percent clay in the fine earth fraction; and
2. have more total clay than an overlying coarser textured horizon (exclusive of differences which result from a lithological discontinuity only) such that:
   - if the overlying horizon has less than 15 percent total clay in the fine earth fraction, the natric horizon must contain at least 3 percent more clay; or
   - if the overlying horizon has 15 percent or more and less than 40 percent total clay in the fine earth fraction, the ratio of clay in the natric horizon to that of the overlying horizon must be 1.2 or greater; or
   - if the overlying horizon has 40 percent or more total clay in the fine earth fraction, the natric horizon must contain at least 8 percent more clay; and
3. have a distinct increase in clay content within a vertical distance of 30 cm if the natric horizon is formed by clay illuviation. Else, the increase in clay content between the overlying and the natric horizon must be reached within a vertical distance of 15 cm; and
4. have no rock structure in at least half the volume of the horizon; and
5. have columnar or prismatic structure in some part of the horizon, or a blocky structure with tongues of an eluvial horizon in which there are uncoated silt or sand grains, extending more than 2.5 cm into the horizon; and
6. have an exchangeable sodium percentage (ESP[8]) greater than 15 within the upper 40 cm of the horizon, or more exchangeable magnesium plus sodium than calcium plus exchange acidity (at pH 8.2) within the same depth if the ESP exceeds 15 percent in some sub horizon within 200 cm from the surface of the soil; and
7. have a thickness of at least one tenth of the sum of the thickness of all overlying horizons, with a minimum value of 7.5 cm.

Note that a coarse(r)-textured horizon overlying the natric horizon must be at least 18 cm thick or 5 cm if the textural transition to the natric horizon is abrupt (see under abrupt textural change).

Nitic horizon

A *nitic* horizon must:

1. have diffuse or gradual transitions to horizons immediately above and below the nitic horizon; and
2. have
   - more than 30 percent clay; and
   - a water-dispersible clay/total clay ratio of less than 0.10 (unless there is more than 0.6 percent organic carbon); and
   - a silt/clay ratio of less than 0.40; and
3. have moderate to strong, nutty or polyhedric structure, with many shiny ped faces; and
4. have no gleyic or stagnic properties; and
5. have
   - 4.0 percent or more citrate-dithionite extractable iron ("free" iron) in the fine earth fraction; and

[8] ESP = exchangeable Na x 100 / CEC.

- more than 0.20 percent acid oxalate (pH 3) extractable ("active") iron in the fine earth fraction; and
- a ratio between "active" and "free" iron of 0.05 or more; and

6. have a thickness of 30 cm or more.

Ochric horizon

An *ochric* horizon lacks fine stratification and has one (or more) of the following characteristics or properties:

1. Consistence is massive and hard or very hard when dry. Very coarse prisms (prisms larger than 30 cm in diameter) are included in the meaning of massive if there is no secondary structure within the prisms; or
2. Both broken and crushed samples have a Munsell chroma of 3.5 or more when moist, and a value of 3.5 or more when moist and 5.5 or more when dry. If there is more than 40 percent finely divided lime, the colour value, moist, must be more than 5; or
3. The organic carbon content is less than 0.6 percent (1 percent organic matter) throughout the (mixed) horizon. The organic carbon content must be less than 2.5 percent if there is more than 40 percent finely divided lime; or
4. The thickness of the horizon is:
   - less than 10 cm if resting directly on hard rock, a petrocalcic, petroduric or petrogypsic horizon, or overlying a cryic horizon; or
   - less than 20 cm or less than one-third of the thickness of the solum where the solum is less than 75 cm thick; or
   - 25 cm or less where the solum is more than 75 cm thick.

Petrocalcic horizon

A *petrocalcic* horizon must:

1. have a calcium carbonate equivalent of 50 percent (by weight) or more; and
2. have cementation to the extent that dry fragments do not slake in water and roots cannot enter; and
3. have extremely hard consistence when dry (cannot be penetrated by spade or auger); and
4. have a thickness of at least 10 cm, or 2.5 cm if it is laminar and rests directly on bedrock.

Petroduric horizon

A *petroduric* horizon must:

1. have cementation or induration in more than 50 percent of the horizon; and
2. show evidence of silica accumulation (opal or other forms of silica) e.g. as coatings in some pores, on some structural faces or as bridges between sand grains; and
3. have less than 50 percent (by volume) of its mass slaking in 1 M HCl even after prolonged soaking, but more than 50 percent slaking in concentrated KOH or in alternating acid and alkali; and
4. be laterally continuous to the extent that roots cannot penetrate except along vertical fractures. The latter must have a horizontal spacing of 10 cm or more; and
5. have a thickness of 10 cm or more.

Petrogypsic horizon

A *petrogypsic* horizon must:

1. contain 60 percent or more gypsum. The percentage gypsum is calculated as the product of gypsum content, expressed as cmol(+) kg^{-1} soil, and the equivalent weight of gypsum (86) expressed as a percentage; and
2. be cemented to the extent that dry fragments do not slake in water and the horizon cannot be penetrated by roots; and
3. have a thickness of 10 cm or more.

Petroplinthic horizon

A *petroplinthic* horizon must:

1. have 10 percent (by weight) or more citrate-dithionite extractable iron, at least in the upper part of the horizon; and
   - have a ratio of acid oxalate (pH 3) extractable iron over citrate-dithionite extractable iron of less than 0.10[9]; and
2. contain less than 0.6 percent (by weight) organic carbon; and
3. be cemented to the extent that dry fragments do not slake in water and the horizon cannot be penetrated by roots; and
4. have a thickness of 10 cm or more.

Plaggic horizon (see Anthropedogenic horizons)

Plinthic horizon

A plinthic horizon must:

1. have 25 percent (by volume) or more of an iron-rich, humus-poor mixture of kaolinitic clay with quartz and other diluents, which changes irreversibly to a hardpan or to irregular, hard aggregates on exposure to repeated wetting and drying with free access of oxygen; and
2. have
   - 2.5 percent (by weight) or more citrate-dithionite extractable iron in the fine earth fraction, especially in the upper part of the horizon, or 10 percent in the mottles or concretions; and
   - a ratio of acid oxalate (pH 3) extractable iron to citrate-dithionite extractable iron of less than 0.10[10]; and
3. contain less than 0.6 percent (by weight) organic carbon; and
4. have a thickness of 15 cm or more.

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[9] Estimated from data given by Varghese and Byju (1993).

[10] Estimated from data given by Varghese and Byju (1993).

Salic horizon

A *salic* horizon must, throughout its depth:

1. have
   - an Electrical Conductivity (ECe) of the saturation extract of more than 15 dS m^{-1} at 25°C at some time of the year; or
   - an ECe of more than 8 dS m^{-1} at 25°C if the $pH_{(H2O)}$ of the saturation extract exceeds 8.5 (for alkaline carbonate soils) or is less than 3.5 (for acid sulphate soils); and
2. have a product of thickness (in cm) times salt percentage of 60 or more; and
3. have a thickness of 15 cm or more.

Spodic horizon

A *spodic* horizon must:

1. have
   - a Munsell hue of 7.5YR or redder with value of 5 or less and chroma of 4 or less when moist and crushed; or
   - a hue of 10YR with value of 3 or less and chroma of 2 or less when moist and crushed; or
   - a sub-horizon, which is 2.5 cm or more thick and which is continuously cemented by a combination of organic matter and aluminium, with or without iron ('thin iron pan'); or
   - distinct organic pellets between sand grains; and
2. contain 0.6 percent or more organic carbon; and
3. have a soil-pH (1:1 in water) of 5.9 or less; and
4. have
   - at least 0.50 percent Al_{ox} + ½Fe_{ox} [11] and have two times or more Al_{ox} + ½Fe_{ox} than an overlying umbric, ochric, albic or anthropedogenic horizon; or
   - an ODOE-value ('Optical Density of the Oxalate Extract') of 0.25 or more, which also is two times or more the value of the overlying horizons; and
5. have a thickness of 2.5 cm or more and an upper limit below 10 cm from the mineral soil surface, unless permafrost is present within 200 cm depth.

Sulfuric horizon

A *sulfuric* horizon must:

1. have a soil-pH < 3.5 (in 1:1 water suspension); and
2. have
   - yellow/orange jarosite [$KFe_3(SO_4)_2(OH)_6$] or yellowish-brown schwertmannite [$Fe_{16}O_{16}(SO_4)_3(OH)_{10}.10H_2O$] mottles; or
   - concretions and/or mottles with a Munsell hue of 2.5Y or more and a chroma of 6 or more; or
   - underlying sulfidic soil materials; or
   - 0.05 percent (by weight) or more of water-soluble sulphate; and
3. have a thickness of 15 cm or more.

[11] Al_{ox} and Fe_{ox}: acid oxalate (pH 3) extractable aluminium and iron, respectively.

Takyric horizon

A **takyric** horizon must:

1. have aridic properties; and
2. have platy or massive structure; and
3. have a surface crust which has all of the following properties:
   - enough thickness (> 5 cm) so that it does not curl entirely upon drying; and
   - polygonal desiccation cracks extending at least 2 cm deep when the soil is dry; and
   - sandy clay loam, clay loam, silty clay loam or finer texture; and
   - very hard consistence when dry and very plastic and sticky consistence when wet.

Terric horizon (see Anthropedogenic horizons)

Umbric horizon

An **umbric** horizon must, after the first 20 cm are mixed, as in ploughing:

1. have
   - structural units with a diameter of 30cm or less or secondary structure with a diameter of 30cm or less (when dry); and/or
   - a moderately hard or softer rupture resistance class (when dry); and
2. have a Munsell colour with a chroma of less than 3.5 when moist and a value darker than 3.5 when moist and 5.5 when dry, both on broken and crushed samples. The colour must be at least one unit darker than that of the C-horizon (both moist and dry) unless the C-horizon has a colour value darker than 4.0, moist, in which case the colour contrast requirement is waived. If a C-horizon is not present, comparison should be made with the horizon immediately underlying the surface horizon; and
3. have a base saturation (in 1 M NH_4OAc at pH 7.0) of less than 50 percent (weighted average throughout the depth of the horizon); and
4. contain, after mixing, 0.6 percent organic carbon (1 percent organic matter) or more throughout. The organic carbon content must be at least 0.6 percent more than that of the C-horizon if the colour requirements are waived because of dark coloured parent materials; and
5. have the following thickness specifications:
   - 10 cm or thicker if resting directly on hard rock, a petroplinthic or petroduric horizon, or overlying a cryic horizon; or
   - 20 cm or more and more than one-third of the thickness of the solum where the solum is less than 75 cm thick; or
   - more than 25 cm where the solum is more than 75 cm thick.

Note that thickness specifications include transitional AB, AE and AC horizons.

Vertic horizon

A **vertic** horizon must:

1. contain 30 percent or more clay throughout; and
2. have wedge-shaped or parallelepiped structural aggregates with the longitudinal axis tilted between 10° and 60° from the horizontal; and

3. have intersecting slickensides[12]; and
4. have a thickness of 25 cm or more.

Vitric horizon

A *vitric* horizon must:

1. have 10 percent or more volcanic glass and other primary minerals in the fine earth fraction; and:
2. have
    - a bulk density > 0.9 kg dm^3; or
    - Al_{ox} + ½Fe_{ox}[13] >0.4 percent; or
    - phosphate retention >25 percent; and
3. have a thickness of 30 cm or more.

Yermic horizon

A *yermic* horizon must:

1. have aridic properties; and
2. have
    - a pavement that is varnished or includes wind-shaped gravel or stones ("ventifacts"); or
    - a pavement and a vesicular crust; or
    - a vesicular crust above a platy A-horizon, without a pavement, or
    - a biological crust, 1 –2 mm thick.

Diagnostic properties

Abrupt textural change

An *abrupt textural change* is indicated by:

- doubling of the clay content within a vertical distance of 7.5 cm if the overlying horizon has less than 20 percent clay; or
- 20 percent (absolute) clay increase within 7.5 cm if the overlying horizon has 20 percent or more clay. In this case some part of the lower horizon should have at least twice the clay content of the upper horizon.

Albeluvic tonguing

Albeluvic tongues must:

1. have the colour of an albic horizon; and

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[12] Slickensides are polished and grooved ped surfaces which are produced by one soil mass sliding past another.

[13] Al_{ox} and Fe_{ox} are acid oxalate (pH 3) extractable aluminium and iron, respectively (method of Blakemore et al., 1987).

2. have greater depth than width, with the following horizontal dimensions:
   - 5 mm or more in clayey argic horizons; or
   - 10 mm or more in clay loamy and silty argic horizons; or
   - 15 mm or more in coarser (silt loam, loam or sandy loam) argic horizons; and
3. occupy more than 10 percent of the volume of the upper 10 cm part of the argic horizon, estimated from or measured on both vertical and horizontal sections; and
4. have a particle size distribution matching that of the eluvial horizon overlying the argic horizon.

Alic properties

Alic properties apply to mineral soil material, which has all of the following physical and chemical characteristics:

1. have a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) equal to or more than 24 cmol(+) kg^{-1} clay; and
2. have
   - a total reserve of bases (TRB = exchangeable plus mineral Ca, Mg, K and Na) of the clay which is 80 percent or more of the TRB of the soil; or
   - a silt/clay ratio of 0.60 or less; and
3. have a pH (KCl) of 4.0 or less; and
4. have a KCl-extractable Al content of 12 cmol(+) kg^{-1} clay or more, and a KCl-extractable Al/CEC_{clay}[14] ratio of 0.35 or more; and
5. have 60 percent aluminium saturation (exch. Al/ECEC x 100) or more.

Aridic properties

Aridic properties are characterized by all of the following:

1. less than 0.6 percent[15] organic carbon if the texture class is sandy loam or finer, or less than 0.2 percent if texture is coarser than sandy loam, as a weighted average in the upper 20 cm of the soil or down to the top of a B-horizon, a cemented horizon, or rock, whichever is shallower; and
2. evidence of aeolian activity in one or more of the following forms:
   - 1 –100 cm long vertical cracks with inblown material. This material has a different colour or a different texture (often sandy) than the soil matrix or a noticeable proportion of rounded or subangular sand particles showing a matt surface; or
   - wind-shaped rock fragments (“ventifacts”) at the surface; or
   - aeroturbation (e.g. crossbedding); or
   - evidence of wind erosion or deposition, or both; or
   - presence of 2% or more of palygorskkite or sepiolite in the clay fraction within a (sub) horizon within 50 cm from the surface, and
3. both broken and crushed samples have a Munsell colour value of 3 or more when moist and 4.5 or more when dry, and a chroma of 2 or more when moist; and
4. a base saturation (in 1 *M* NH_4OAc at pH 7.0) of more than 75 percent (normally 100 percent; this requirement is waived in lime-free Gypsisols).

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[14] CEC_{clay}: cation exchange capacity (by 1 M NH_4OAc) of the clay fraction, corrected for organic matter.

[15] The organic carbon content may be higher if the soil is periodically flooded, or if it has an electrical conductivity of the saturated paste extract of 4 dS m^{-1} or more somewhere within 100 cm of the soil surface.

Continuous hard rock

Continuous hard rock is material underlying the soil, exclusive of cemented pedogenetic horizons such as a petrocalcic, petroduric, petrogypsic and petroplinthic horizons, which is sufficiently coherent and hard when moist to make hand digging with a spade impracticable. The material is still considered continuous if only a few cracks 10 cm or more apart are present and no significant displacement of the rock has taken place.

Ferralic properties

Ferralic properties apply to mineral soil materials, which have:

- a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) of less than 24 cmol(+) kg^{-1} clay; or
- a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) of less than 4 cmol(+) kg^{-1} soil, in at least some subhorizon of the B-horizon or in the horizon immediately underlying the A-horizon.

Geric properties

Geric properties apply to mineral soil materials, which have:

- 1.5 cmol(+) or less of [exchangeable bases (Ca, Mg, K, Na) plus unbuffered 1 *M* KCl exchangeable acidity] per kg clay; or
- a delta pH (pH_{KCl} minus pH_{water}) of +0.1 or more.

Gleyic properties

Gleyic properties signify the occurrence of reducing conditions[16] , evidenced by:

1. an rH-value in the soil solution of 19 or less; or
2. presence of free Fe^{2+} shown by a strong red colour after spraying a freshly broken surface of a field-wet soil sample it with a solution of 9.2% a,a dipyridyl in 10% acetic acid; and
3. a gleyic colour pattern[17] reflecting oximorphic[18] and/or reductomorphic[19] properties,
   - in more than 50 percent of the soil mass; or
   - in 100 percent of the soil mass below any surface horizon.

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[16] The basic measure for reduction in soil materials is the rH. This measure is related to the redox potential (Eh) and corrected for the pH, as shown in the following formula:

$$rH = \frac{Eh(mV)}{29} + 2pH$$

[17] A *gleyic colour pattern* results from a redox gradient between the groundwater and capillary fringe, causing an uneven distribution of iron and manganese (hydr)oxides. In the lower part of the soil and/ or inside the peds the oxides are either transformed into insoluble Fe/Mn(II) compounds or they are translocated, both processes leading to the absence of colours with a Munsell hue redder than 2.5Y. Translocated iron and manganese compounds can be concentrated in oxidized form (Fe(III), Mn(IV)), recognizable by a 10% H_2O_2 test in the field, on ped surfaces or in (bio)pores ("rusty root channels"), and towards the surface even in the matrix.

Permafrost

Permafrost denotes a soil layer in which the temperature is continually at or below 0°C for at least two consecutive years.

Secondary carbonates

Secondary carbonates are translocated lime, soft enough to be cut readily with a finger nail, precipitated the soil solution rather than inherited from a soil parent material. As a diagnostic property it should be present in significant quantities.

Field identification. Secondary carbonates must have some relation to the soil structure or fabric. Secondary carbonate accumulations may disrupt the fabric to form spheroidal aggregates or 'white eyes', that are soft and powdery when dry, or secondary carbonates may be present as soft coatings in pores or on structural faces. If present as coatings, secondary carbonates cover 50 percent or more of the structural faces and are thick enough to be visible when moist. If present as soft nodules, they occupy 5 percent or more of the soil volume. Filaments (*pseudomycelia*), which come and go with changing moisture conditions, are not included in the definition of secondary carbonates.

Stagnic properties

Stagnic properties are indicative of reducing conditions, evident from:

1. a value of rH in the soil solution of 19 or less; or
2. presence of free Fe^{2+} as shown by the appearance of a strong red colour on a freshly broken surface of a field-wet soil sample after spraying it with a 9.2% a,a dipyridyl solution in 10% acetic acid; and
3. an albic horizon or a stagnic colour pattern
   - in more than 50 percent of the soil volume if the soil is undisturbed; or
   - in 100 percent of the soil volume if the surface horizon is disturbed by ploughing.

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[18] *Oximorphic properties* reflect alternating reducing and oxidizing conditions, as is the case in the capillary fringe and in the surface horizon(s) of soils with fluctuating groundwater levels. Oximorphic properties are expressed by reddish brown (ferrihydrite) or bright yellowish brown (goethite) mottles, or as bright yellow (jarosite) mottles in acid sulphate soils. In loamy and clayey soils, the iron (hydr)oxides are concentrated on aggregate surfaces and the walls of larger pores (e.g. old root channels).

[19] *Reductomorphic properties* reflect permanently wet conditions, and are expressed by neutral (white to black: N1/ to N8/) or bluish to greenish (2.5Y, 5Y, 5G, 5B) colours in more than 95 percent of the soil matrix. In loamy and clayey material blue-green colours dominate due to Fe (II,III) hydroxy salts ("green rust"). If the material is rich in sulphur blackish colours prevail due to iron sulphides. In calcareous material whitish colours are dominant due to calcite and/or siderite. Sands are usually light grey to white in colour and often also impoverished in iron and manganese. The upper part of a reductomorphic horizon may show up to 5 percent rusty colours, mainly around channels of burrowing animals or plant roots.

Strongly humic properties

To be *strongly humic*, soil material must have more than 1.4 percent organic carbon as weighted average over a depth of 100 cm from the soil surface (the same weighted average over 100 cm applies if the soil is 50-100 cm deep; soils less than 50 cm deep cannot be strongly humic). The calculation assumes a bulk density of 1.5 g cm^{-3}.

Vertic properties

To have *vertic properties*, a soil must:

1. have, after the upper 20 cm are mixed, 30 percent or more clay throughout upper 50 cm, and
2. have
   - intersecting slickensides, and/or
   - cracks, which open and close periodically, extend down to 50 cm from the soil surface or deeper and are 1cm or more wide at the surface.

Diagnostic materials

Anthropomorphic soil material

Anthropomorphic soil material (from Gr. *anthropos*, human) is unconsolidated mineral or organic material resulting (largely) from human activities. Anthropomorphic soil material has not, however, been subject to a sufficiently long period of soil formation to acquire distinct signs of pedogenetic alteration.

The following anthropomorphic soil materials are currently distinguished:

Aric soil material has 3 percent or more (by volume) fragments of diagnostic horizons, which are not arranged in any discernible order.

Garbic soil material is organic waste material as found in landfills containing dominantly organic waste products.

Reductic soil material refers to presence of waste products producing gaseous emissions (e.g. methane, carbon dioxide) resulting in anaerobic conditions in the material.

Spolic soil material refers to presence of material originating from industrial activities (mine spoil, river dredgings, highway constructions, etc.).

Urbic soil material refers to soil material containing more than 35 percent (by volume) of building rubble and artefacts.

Calcaric soil material

Calcaric soil material (from En. *calcareous*) shows strong effervescence in contact with 10 percent HCl. In practice, calcaric soil material contains more than 2 percent calcium carbonate equivalent.

Fluvic soil material

Fluvic soil material (from L. *fluvius*, river) is soil material, which shows stratification in at least 25 percent of the soil volume. Stratification is surmised if the organic carbon content decreases irregularly with depth but remains greater than 0.2 percent to a depth of 100 cm. Thin strata of sand may contain less organic carbon if underlying finer sediments, exclusive of buried A-horizons, contain more than 0.2 percent organic carbon. Fluvic soil material must be associated with structural water bodies (seas, lakes and rivers).

Gypsiric soil material

Gypsiric soil material (from L. *gypsum*) is mineral soil material, which contains 5 percent or more gypsum (by volume).

Organic soil material

Organic soil material must:

if saturated with water for long periods (unless artificially drained and excluding live roots), have:

- 18 percent organic carbon (30 percent organic matter) or more if the mineral fraction consists for 60 percent or more of clay; or
- 12 percent organic carbon (20 percent organic matter) or more if the mineral fraction has no clay; or
- an carbon content between 12 and 18 percent, proportional to the clay content, if the clay content of the mineral fraction is between 0 and 60 percent; or

if never saturated with water for more than a few days, have 20 percent or more organic carbon.

Sulfidic soil material

Sulfidic soil material must:

1. have 0.75 percent or more sulphur (dry weight) and less than three times more calcium carbonate equivalent than sulphur; and
2. have a soil-$pH_{(H2O)}$ in excess of 3.5.

Tephric soil material

Tephric soil material must:

1. have 60 percent or more tephra; and
2. have less than 0.4 percent Al + ½Fe, extractable in acid oxalate (pH 3).

Annex 3
Qualifiers (formative elements for naming soil units)

General rules

1. Soil units are defined by one or more '*qualifiers'*. Each qualifier has a unique meaning.
2. Qualifiers are described in terms of established diagnostic horizons, properties and characteristics but may include additional (new) elements.
3. Qualifier definitions must not contain criteria referring to climate, parent material, vegetation, physiographic features, soil-water relationships or characteristics/properties of the substratum (below the control section).
4. Not more than two qualifiers may be used in soil unit names. If additional qualifiers are needed, these must follow the Reference Soil Group name between brackets, e.g. Acri Geric Ferralsol (Humic and Xanthic).
5. Qualifiers used in a soil unit name may not overlap or conflict nor may qualifiers used in a soil name overlap or conflict with the definition of the Reference Soil Group to which the qualifiers are attached. For instance, a Dystri-Petric Calcisol is a contradiction ('Dystri' clashes with 'Calcisol') whereas a Eutric-Petri Calcisol is an overlap because the prefix 'Eutric' adds no information beyond the specifications of the Calcisol Reference Group.

Definitions of qualifiers

Abruptic having an *abrupt textural change*.

Aceric having, within 100 cm from the soil surface, a pH (1:1 in water) between 3.5 and 5 and jarosite mottles *(in Solonchaks only)*.

Acric having, in at least part of the subsurface horizon within 100 cm from the soil surface, a *ferralic* horizon, which meets the clay increase requirements of an *argic* horizon, and has less than 50 percent base saturation (in 1 *M* NH_4OAc at pH 7.0) *(in Ferralsols only)*.

Acroxic having, within 100 cm from the soil surface, less than 2 cmol(+) kg^{-1} of (exchangeable bases plus 1 *M* KCl exchangeable Al^{3+}) in the fine earth fraction of one or more horizons with a combined thickness of 30 cm or more *(in Andosols only)*.

Albic having, within 100 cm from the soil surface, an *albic* horizon.

- **Hyperalbic** having an *albic* horizon within 50 cm from the soil surface and the lower boundary at a depth of 100 cm or more from the soil surface.
- **Glossalbic** having tonguing of an *albic* into an *argic* or *natric* horizon.

TABLE 3
Alphabetical list of Qualifiers.

	Abruptic		Ferralic		Lixic		Rhodic
	Aceric		Ferric		Luvic		Rubic
	Acric		Fibric		Magnesic		Ruptic
	Acroxic		Folic		Mazic		Rustic
	Albic		Fluvic		Melanic		Salic
	Alcalic		Fragic		Mesotrophic		Sapric
	Alic		Fulvic		Mollic	100	Siltic
	Alumic		Garbic	70	Natric		Skeletic
	Andic	40	Gelic		Nitic		Sodic
10	Anthraquic		Gelistagnic		Ochric		Spodic
	Anthric		Geric		Ombric		Spolic
	Anthropic		Gibbsic		Oxyaquic		Stagnic
	Arenic		Glacic		Pachic		Sulphatic
	Aric		Gleyic		Pellic		Takyric
	Aridic		Glossic		Petric		Tephric
	Arzic		Greyic		Petrocalcic		Terric
	Calcaric		Grumic		Petroduric	110	Thionic
	Calcic		Gypsic	80	Petrogypsic		Toxic
	Carbic	50	Gypsiric		Petroplinthic		Turbic
20	Carbonatic		Haplic		Petrosalic		Umbric
	Chernic		Histic		Placic		Urbic
	Chloridic		Hortic		Plaggic		Vetic
	Chromic		Humic		Planic		Vermic
	Cryic		Hydragric		Plinthic		Vertic
	Cutanic		Hydric		Posic		Vitric
	Densic		Hyperochric		Profondic		Xanthic
	Duric		Hyperskeletic		Protic	120	Yermic
	Dystric		Irragric	90	Reductic		
	Entic	60	Lamellic		Regic		
30	Eutric		Leptic		Rendzic		
	Eutrisilic		Lithic		Rheic		

Where relevant, names can be defined further using prefixes, for example Epigleyi-, Protothioni-. The following prefixes can be used:

Bathi	Epi	Orthi	Thapto
Cumuli	Hyper	Para	
Endo	Hypo	Proto	

Alcalic having, within 50 cm from the surface, soil material, which has in a 1:1 aqueous solution, a pH of 8.5 or more.

Alic having an *argic* horizon, which has a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) equal to or greater than 24 cmol(+) kg^{-1} clay throughout, a silt/clay ratio of less than 0.6, and 50 percent or more Al-saturation.

Alumic having, in at least some part of the subsurface horizon between 50 and 100 cm from the soil surface, 50 percent or more Al-saturation.

Andic having, within 100 cm from the soil surface, an *andic* horizon.

- **Aluandic** Andic with less than 0.6 percent acid oxalate (pH 3) extractable silica, or an Al_{py}[1]/Al_{ox}[2] ratio of 0.5 or greater.
- **Silandic** Andic with 0.6 percent or more acid oxalate (pH 3) extractable silica, or an Al_{py}/Al_{ox} ratio of less than 0.5.

Anthraquic having an *anthraquic* horizon.

Anthric showing evidence of alteration by cultivation practices.

Anthropic showing evidence of profound modification of the soil by human activity other than cultivation *(in Regosols only)*.

Aric having remnants of diagnostic horizons disturbed by repeated deep ploughing.

Arenic having, throughout the upper 50 cm soil layer, a texture of loamy fine sand or coarser.

Aridic having *aridic* properties ***and*** not having a *takyric* or *yermic* horizon.

Arzic having, within 50 cm from the soil surface, sulphate-rich groundwater at some period in most years ***and*** having, averaged over a depth of 100 cm, 15 percent or more gypsum *(in Gypsisols only)*.

Calcaric calcareous at least between 20 and 50 cm from the soil surface.

Calcic having, between 50 and 100 cm from the soil surface, a *calcic* horizon or concentrations of *secondary carbonates*.

- **Hypercalcic** having a *hypercalcic* horizon, which contains 50 percent or more calcium carbonate equivalent.
- **Hypocalcic** having only concentrations of *secondary carbonates* within 100 cm from the soil surface.
- **Orthicalcic** having a *calcic* horizon within 100 cm from the soil surface.

Carbic having a cemented *spodic* horizon, which does not contain sufficient amorphous iron to turn redder on ignition *(in Podzols only)*.

Carbonatic having, in a 1:1 aqueous solution, a soil-pH > 8.5 ***and*** $HCO_3 > SO_4 >> Cl$ *(in Solonchaks only)*.

Chernic having a *chernic* horizon *(in Chernozems only)*.

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1 Al_{py}: pyrophosphate extractable aluminium.
2 Al_{ox}: acid oxalate (pH 3) extractable aluminium.

Chloridic having, in a 1:1 aqueous solution, $Cl >> SO_4 > HCO_3$ *(in Solonchaks only)*.

Chromic having a subsurface horizon, which in the major part has a Munsell hue of 7.5YR and a chroma (moist) greater 4, or a hue (moist) redder than 7.5YR.

Cryic having, within 100 cm from the soil surface, a *cryic* horizon.

Cutanic having clay skins in the argic horizon.

Densic having a cemented *spodic* horizon ("Ortstein") *(in Podzols only)*.

Duric having, within 100 cm from the soil surface, a *duric* horizon.
Hyperduric having a *duric* horizon containing more than 50 percent silica.

Dystric having, in at least some part between 20 and 100 cm from the soil surface, or in a layer 5 cm thick directly above a lithic contact in *Leptosols,* a base saturation (in 1 *M* NH_4OAc at pH 7.0) of less than 50 percent.
Epidystric Dystric, having a base saturation (in 1 *M* NH_4OAc at pH 7.0) of less than 50 percent at least between 20 and 50 cm from the soil surface.
Hyperdystric Dystric, having a base saturation (in 1 *M* NH_4OAc at pH 7.0) of less than 50 percent in all parts between 20 and 100 cm from the soil surface, and less than 20 percent in some part within 100 cm from the soil surface.
Orthidystric Dystric, having a base saturation (in 1 *M* NH_4OAc at pH 7.0) of less than 50 percent in all parts between 20 and 100 cm from the soil surface.

Entic having no *albic* horizon and having a loose *spodic* horizon *(in Podzols only)*.

Eutric having, at least between 20 and 100 cm from the soil surface, or in a layer 5cm thick directly above a lithic contact in *Leptosols,* a base saturation (in 1 *M* NH_4OAc at pH 7.0) of 50 percent or more.
Endoeutric Eutric, having a base saturation (in 1 *M* NH_4OAc at pH 7.0) of 50 percent or more in all parts between 50 and 100 cm from the soil surface.
Hypereutric Eutric, having a base saturation (in 1 *M* NH_4OAc at pH 7.0) of 80 percent or more in all parts between 20 and 100 cm from the soil surface.
Orthieutric Eutric, having a base saturation (in 1 *M* NH_4OAc at pH 7.0) of 50 to 80 percent in all parts between 20 and 100 cm from the soil surface.

Eutrisilic having a *silandic* horizon and a sum of exchangeable bases equal to or than 25 cmol(+) kg^{-1} fine earth within 30 cm from the soil surface.

Ferralic having, within 100 cm from the soil surface, *ferralic* properties.

Hyperferralic Ferralic, having a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) of less than 16 cmol(+) kg^{-1} clay in at least some part within 100 cm from the soil surface.

Hypoferralic Ferralic, having a cation exchange capacity (in 1 *M* NH_4OAc at pH 7.0) of less than 4 cmol(+) kg^{-1} fine earth in at least 30 cm of the upper 100 cm of the soil, and a Munsell colour chroma (moist) of 5 or more and/or hues redder than 10YR *(in Arenosols only)*.

Ferric having, within 100 cm from the soil surface, a *ferric* horizon.

Hyperferric Ferric**,** having, within 100 cm from the soil surface, one or more layers with a total thickness of 25 cm or more consisting of 40 percent or more iron/manganese-oxide nodules.

Fibric having more than two-thirds (by volume) of the *organic* soil material consisting of recognisable plant tissue *(in Histosols only)*.

Folic having a *folic* horizon *(in Histosols only)*.

Fluvic having, within 100 cm from the soil surface, *fluvic* soil material.

Fragic having, within 100 cm from the soil surface, a *fragic* horizon.

Fulvic having, within 30 cm from the soil surface, a *fulvic* horizon.

Garbic having soil material containing more than 35 percent (by volume) organic waste materials *(in Anthropic Regosols only)*.

Gelic having, within 200 cm from the soil surface, *permafrost*.

Gelistagnic having temporary water saturation at the surface caused by frozen subsoil.

Geric having, in at least some horizon within 100 cm from the soil surface, *geric* properties.

Gibbsic having, within 100 cm from the soil surface, a layer more than 30 cm thick containing more than 25 percent gibbsite in the fine earth fraction.

Glacic having, within 100 cm from the soil surface, a layer more than 30 cm thick and containing 95 percent or more ice (by volume).

Gleyic having, within 100 cm from the soil surface, *gleyic* properties.

Endogleyic having *gleyic* properties between 50 and 100 cm from the soil surface.

Epigleyic having *gleyic* properties within 50 cm from the soil surface.

Glossic having tonguing of a *mollic* or *umbric* horizon into an underlying subsurface horizon or into the saprolite.

- **Molliglossic** having tonguing of a *mollic* horizon into an underlying subsurface horizon or into the saprolite.
- **Umbriglossic** having tonguing of an *umbric* horizon into an underlying subsurface horizon or into the saprolite.

Greyic having uncoated silt and sand grains on structural ped faces in a *mollic* horizon *(in Phaeozems only)*.

Grumic having a surface layer with a thickness of 3 cm or more with a strong structure finer than very coarse granular *(in Vertisols only)*.

Gypsic having, within 100 cm from the soil surface, a *gypsic* horizon.

- **Hypergypsic** having a *gypsic* horizon, which has 60 percent or more gypsum.
- **Hypogypsic** having a *gypsic* horizon, which has 25 percent or less gypsum.

Gypsiric having, at least between 20 and 50 cm from the soil surface, *gypsiric* soil material.

Haplic having the typical expression of the Soil Reference Group in the sense that there is no further or meaningful characterisation.

Histic having, within 40 cm from the soil surface, a *histic* horizon.

- **Fibrihistic** having, within 40 cm from the soil surface, a *histic* horizon, in which more than two-thirds (by volume) of the *organic* soil material consist of recognisable plant tissue.
- **Saprihistic** having, within 40 cm from the soil surface, a *histic* horizon, in which less than one-sixth (by volume) of the *organic* soil material consists of recognisable plant tissue.
- **Thaptohistic** having a buried *histic* horizon between 40 and 100 cm from the soil surface.

Hortic having a *hortic* horizon, which is 50 cm or more thick in *Anthrosols* or less than 50 cm thick in other soils.

Humic having, over a depth of 100 cm from the soil surface, more than 1.4 percent organic carbon (by weight) in the fine earth fraction in *Ferralsols* or *Nitisols*, ***or***
having more than 2 percent organic carbon (by weight) to a depth of 25 cm in *Leptosols*, ***or***
having more than 1 percent organic carbon (by weight) to a depth of 50 cm in other soils.

Hydragric having an *anthraquic* horizon ***and*** an associated *hydragric* horizon, the latter occurring within 100 cm from the soil surface *(in Anthrosols only)*.

Hydric having, within 100 cm from the soil surface, one or more layers with a total thickness of 35 cm or more, which have (in undried samples) a water retention at 1500 kPa of 100 percent or more *(in Andosols only)*.

Hyperskeletic having, to a depth of 75 cm or more or to continuous hard rock, more than 90 percent (by weight) gravel or other coarse fragments *(in Leptosols only)*.

Irragric having an *irragric* horizon, which is 50 cm or more thick in *Anthrosols* or less than 50 cm thick in other soils.

Lamellic having, within 100 cm from the soil surface, clay illuviation lamellae with a combined thickness of 15 cm or more.

Leptic having, between 25 and 100 cm from the soil surface, *continuous hard rock*.

- **Endoleptic** having *continuous hard rock* between 50 and 100 cm from the soil surface.
- **Epileptic** having *continuous hard rock* between 25 and 50 cm from the soil surface.
- **Paraleptic** having, at least between 25 and 50 cm from the soil surface, a dense heavy clayey layer that is impenetrable to roots.

Lithic having, within 10 cm from the soil surface, *continuous hard rock*.

- **Paralithic** having, within 10 cm from the soil surface, a broken rock contact with fissures less than 10 cm apart, which allow roots to penetrate the underlying rock.
- **Hypolithic** having, within 10 cm from the soil surface, continuous rock with a hardness of less than 3.

Lixic having a *ferralic* horizon, which meets the clay increase requirements of an *argic* horizon, and which has a base saturation (in 1 *M* NH_4OAc at pH 7.0) of 50 percent or more throughout the *ferralic* horizon to a depth of 100 cm from the soil surface *(in Ferralsols only)*.

Luvic having an *argic* horizon, which has a cation exchange capacity equal to or greater than 24 cmol(+) kg^{-1} clay (in 1 *M* NH_4OAc at pH 7.0) throughout, and a base saturation of 50 percent or more throughout the horizon to a depth of 100 cm from the soil surface.

- **Hypoluvic** Luvic, having an (absolute) clay increase of 3 percent or more within 100 cm from the soil surface *(in Arenosols only)*.

Magnesic having, within 100 cm from the soil surface, a ratio of exchangeable Ca/Mg of less than 1

Mazic having, in the upper 20 cm soil layer, a massive structure and hard to very hard consistence *(in Vertisols only)*.

Melanic having a *melanic* horizon *(in Andosols only)*.

Mesotrophic having, at 20 cm depth, a base saturation (in 1 *M* NH_4OAc at pH 7.0) of less than 75 percent *(in Vertisols only)*.

Mollic having a *mollic* horizon.

Natric having, within 100cm from the soil surface, a *natric* horizon.

Nitic having, within 100cm from the soil surface, a *nitic* horizon.

Ochric having an *ochric* horizon.

Hyperochric having an *ochric* horizon, which is grey when dry and turns darker on moistening and which contains less than 0.4 percent organic carbon (by weight) and has little free iron oxide, coarse texture, platy structure and a thin surface crust.

Ombric having a water regime conditioned by surplus precipitation (over evaporation) during most of the year *(in Histosols only)*.

Oxyaquic being saturated with water during the thawing period and lacking *oximorphic* and/or *reductomorphic* properties within 100 cm from the soil surface *(in Cryosols only)*.

Pachic having a *mollic* or an *umbric* horizon more than 50 cm thick.

Pellic having, in the upper 30 cm of the (moist) soil matrix, a Munsell value of 3.5 or less and a chroma of 1.5 or less *(in Vertisols only)*.

Petric strongly cemented or indurated within 100 cm from the soil surface.

Endopetric strongly cemented or indurated between 50 and 100 cm from the soil surface.

Epipetric strongly cemented or indurated within 50 cm from the soil surface.

Petrocalcic having, within 100 cm from the soil surface, a *petrocalcic* horizon.

Petroduric having, within 100 cm from the soil surface, a *petroduric* horizon.

Petrogypsic having, within 100 cm from the soil surface, a *petrogypsic* horizon.

Petroplinthic having, within 100 cm from the soil surface, a *petroplinthic* horizon.

Petrosalic having, within 100 cm from the soil surface, a horizon 10 cm or more thick, which is cemented by salts more soluble than gypsum.

Placic having, within 100 cm from the soil surface, a sub-horizon of the *spodic* horizon, which is 1 cm or more thick and which is cemented by a combination of organic matter and aluminium, with or without iron ("thin iron pan"; *in Podzols only)*.

Plaggic having a *plaggic* horizon, which is 50 cm or more thick in *Anthrosols* or less than 50 cm thick in other soils.

Planic having, within 100 cm from the soil surface, an eluvial horizon abruptly overlying a slowly permeable horizon.

Plinthic having, within 100 cm from the soil surface, a *plinthic* horizon.

- **Epiplinthic** having a *plinthic* horizon within 50 cm from the soil surface.
- **Hyperplinthic** having a *plinthic* horizon in which irreversible hardening results in a continuous sheet of ironstone.
- **Orthiplinthic** having a *plinthic* horizon in which irreversible hardening results in a layer of gravel-sized ironstone (*"pisoliths"* or *"pea iron"*).
- **Paraplinthic** having a mottled horizon with at least 10 percent (by volume) iron nodules resembling a *plinthic* horizon but which does not irreversibly harden on repeated drying and wetting.

Posic having, within 100 cm from the soil surface, a zero or positive charge (pH_{KCl} - pH_{water}) in a layer more than 30 cm thick *(in Ferralsols only)*.

Profondic having an *argic* horizon in which the clay content does not decrease by more than 20 percent (relative) from its maximum within 150 cm from the soil surface.

Protic having no appreciable soil horizon development *(in Arenosols only)*.

Reductic having evidence of anaerobic conditions caused by gaseous emissions (e.g. methane, carbon dioxide) *(in Anthropic Regosols only)*.

Regic lacking recognisable buried horizons *(in Anthrosols only)*.

Rendzic having a *mollic* horizon, which is between 10 and 25 cm thick and contains or immediately overlies *calcaric soil material* having more than 40 percent calcium carbonate equivalent *(in Leptosols only)*.

Rheic having a water regime conditioned by surface water *(in Histosols only)*.

Rhodic having a subsurface horizon with a Munsell hue of 3.5YR or redder in all parts (apart from transitional horizons to A and C-horizons), a moist colour value of less than 3.5 and a dry colour value no more than one unit higher than the moist value.

Rubic having a subsurface horizon with a Munsell hue redder than 10YR and or a moist chroma of 5 or more *(in Arenosols only)*.

Ruptic having, within 100 cm from the soil surface, a lithological discontinuity.

Rustic having a cemented *spodic* horizon, which turns redder on ignition, underlies an *albic* horizon and lacks a sub-horizon, which is 2.5 cm or more thick and which is continuously cemented by a combination of organic matter and aluminium, with or without iron ("thin iron pan") *(in Podzols only)*.

Salic having, within 100 cm from the soil surface, a *salic* horizon.

- **Endosalic** having a *salic* horizon between 50 and 100 cm from the soil surface.
- **Episalic** having a *salic* horizon between 25 and 50 cm from the soil surface.
- **Hyposalic** having, in at least some sub-horizon within 100 cm from the soil surface, an ECe-value (electric conductivity of the saturation extract) greater than 4 dS m^{-1} at $25^{o}C$.
- **Hypersalic** having, in at least some sub-horizon within 100 cm from the soil surface, an ECe-value (electric conductivity of the saturation extract) greater than 30 dS m-1 at 25 ^{o}C.

Sapric having, after rubbing, less recognisable plant tissue than one-sixth (by volume) of the *organic* soil material *(in Histosols only)*.

Siltic having, within 100 cm from the soil surface, a layer more than 30 cm thick and containing 40 percent or more silt.

Skeletic having, to a depth of 100 cm from the soil surface, between 40 and 90 percent (by weight) gravel or other coarse fragments.

- **Endoskeletic** having, between 50 and 100 cm from the soil surface, between 40 and 90 percent (by weight) gravel or other coarse fragments.
- **Episkeletic** having, between 20 and 50 cm from the soil surface, between 40 and 90 percent (by weight) gravel or other coarse fragments.

Sodic having, within 50 cm from the soil surface, more than 15 percent exchangeable sodium or more than 50 percent exchangeable sodium plus magnesium.

- **Endosodic** having, between 50 and 100 cm from the soil surface, more than 15 percent exchangeable sodium or more than 50 percent exchangeable sodium plus magnesium.
- **Hyposodic** having, within 100 cm from the soil surface, more than 6 percent exchangeable sodium in at least some sub-horizon more than 20 cm thick.

Spodic having a *spodic* horizon.

Spolic having soil material containing more than 35 percent (by volume) industrial waste, e.g. mine spoil, dredge spoil, etc. *(in Anthropic Regosols only)*.

Stagnic having *stagnic* properties within 50 cm from the soil surface.
Endostagnic having *stagnic* properties between 50 and 100 cm from the soil surface.

Sulphatic having, in a 1:1 aqueous solution, SO_4 >> HCO_3 > Cl *(in Solonchaks only)*.

Takyric having a *takyric* horizon.

Tephric having, to a depth of 30 cm or more from the soil surface, *tephric* soil material.

Terric having a *terric* horizon, which is 50 cm or more thick in *Anthrosols* or less than 50 cm thick in other soils.

Thionic having, within 100 cm from the soil surface, a *sulfuric* horizon or *sulfidic* soil material.
Orthithionic having a *sulfuric* horizon within 100 cm from the soil surface.
Protothionic having *sulfidic* soil material within 100 cm from the soil surface.

Toxic having, within 50 cm from the soil surface, ions other than aluminium, iron, sodium, calcium or magnesium, in concentrations toxic to plants.

Turbic having, either at the surface or within 100 cm from the soil surface, features resulting from cryoturbation. These include mixed soil material, disrupted soil horizons, involutions (swirl-like patterns in soil horizons), organic intrusions, frost heave, separation of coarse from fine soil materials, cracks and patterned surface features such as earth hummocks, frost mounds, stone circles, nets and polygons *(in Cryosols only)*.

Umbric having an *umbric* horizon.

Urbic having soil material containing more than 35 percent (by volume) earthy materials mixed with building rubble and artefacts *(in Anthropic Regosols only)*.

Vermic having, in the upper 100 cm of the soil or down to rock or to a *petrocalcic*, *petroduric*, *petrogypsic* or *petroplinthic* horizon, whichever is shallower, 50 percent or more (by volume) wormholes, worm casts, and/or filled animal burrows.

Vertic having, within 100 cm from the soil surface, a *vertic* horizon or *vertic* properties.

Vetic having, in at least some part of the subsurface horizon within 100 from the soil surface, less than 6 cmol(+) kg^{-1} clay of (exchangeable bases plus exchangeable acidity).

Vitric having, within 100 cm from the soil surface, a *vitric* horizon ***and*** having no *andic* horizon overlying the *vitric* horizon.

Xanthic having a *ferralic* horizon with a yellow to pale yellow colour (rubbed soil has Munsell hues of 7.5YR or yellower with a value, moist, of 4 or more and a chroma, moist, of 5 or more).

Yermic having a *yermic* horizon including a desert pavement.
Nudiyermic having a *yermic* horizon without a desert pavement.

Prefixes

The following prefixes may be used to indicate depth of occurrence or degree of expression of soil characteristics or properties. Prefixes are combined with other elements to one word, e.g. Orthicalcic. A double combination, e.g. Epihypercalcic, is allowed.

Bathi horizon, property or material starting between 100 and 200 cm from the soil surface.

Cumuli having repetitive accumulation of soil material of 50 cm or more in the surface or A-horizon.

Endo horizon, property or material starting between 50 and 100 cm from the soil surface.

Epi horizon, property or material starting within 50 cm from the soil surface.

Hyper having excessive or strong expression.

Hypo having slight or weak expression.

Orthi having an expression that is typical for the feature (typical in the sense that there is no further or meaningful characterisation).

Para having resemblance to a particular feature (e.g. Paralithic).

Proto indicating a precondition or an early stage of development (e.g. Protothionic).

Thapto having, within 200 cm from the soil surface, a buried horizon or a buried soil (given in combination with the buried diagnostic horizon, e.g. Thaptomollic).

Annex 4 Suggestions for ranking qualifiers in soil unit names[1]

The following suggestions for ranking *qualifiers* in Soil Unit names address only the most common qualifiers found in each Reference Soil Group. The suggested ranking orders are based on the following considerations:

- *"strong expression qualifiers",* if any, have the highest priority;
- *"intergrade qualifiers",* if any, are added next;
- *"secondary characteristics qualifiers"* that refer to defined diagnostic horizons, properties or soil materials are added next, and precede
- *"secondary characteristics qualifiers"* that are not directly related to defined diagnostic horizons, properties or soil materials (qualifiers referring to soil colour have the lowest priority); and
- *the "haplic" qualifier* is considered last.

Strong expression qualifiers

"Strong expression qualifiers" indicate which diagnostic criteria of the Soil Reference Group are strongly expressed in a particular soil profile. The following overview is tentative:

Qualifier	*Reference Soil Group(s)*	*Qualifier*	*Reference Soil Group(s)*
Turbic, Glacic	Histosols, Cryosols	Petroplinthic	Plinthosols
Hydragric, Irragric, Terric, Plaggic, Hortic	Anthrosols	Gibbsic, Geric, Posic	Ferralsols
Lithic, Hyperskeletic Rendzic	Leptosols	Chernic	Chernozems, Phaeozems
Thionic	Histosols, Vertisols, Fluvisols, Gleysols, Planosols, Umbrisols, Cambisols	Petrogypsic, Hypergypsic	Gypsisols
Vitric, Silandic, Aluandic, Eutrisilic, Melanic, Fulvic, Hydric	Andosols	Petroduric	Durisols
Densic, Carbic, Rustic	Podzols	Petrocalcic, Hypercalcic	Calcisols

Intergrade qualifiers

"Intergrade qualifiers' indicate a diagnostic horizon, property or soil material additional to the horizon(s), property/properties or material(s) whose presence of absence determined the Soil Reference Group and indicate that the soil holds an intermediate position between Groups.

[1] This Annex was contributed by F. Berding.

Qualifier	*Intergrade to*	*Qualifier*	*Intergrade to*	*Qualifier*	*Intergrade to*
Histic	Histosols	Andic	Andosols	Calcic	Calcisols
Cryic	Cryosols	Spodic	Podzols	Albic	Albeluvisols
Gelic	Cryosols	Plinthic	Plinthosols	Alic	Alisols
Anthric[1]	Anthrosols	Ferralic[3]	Ferralsols	Nitic	Nitisols
Leptic	Leptosols	Natric[4]	Solonetz	Acric	Acrisols
Vertic	Vertisols	Planic	Planosols	Luvic	Luvisols
Fluvic	Fluvisols	Mollic	Cherno-, Kastano- and Phaeozems	Lixic	Lixisols
Salic[2]	Solonchaks			Umbric	Umbrisols
Gleyic	Gleysols	Gypsic	Gypsisols	Arenic	Arenosols
Vitric	Andosols	Duric	Durisols	Regic[5]	Regosols

1 Anthric refers to the presence of anthropedogenic horizons (Anthraquic, Hortic, Irragric, Plaggic and Terric) that are less than 50 cm thick; qualifiers used indicate the particular kind of anthropedogenic horizon, e.g. 'Plaggic Podzol' instead of 'Anthric Podzol'.

2 Salic is used instead of "Solonchakic"; intergrade qualifiers are not further subdivided (e.g. in Episalic or Hyposalic).

3 Ferralic does not indicate the presence of a ferralic horizon but of ferralic properties.

4 Natric is used instead of "Solonetzic.

5 Regic, also to indicate the absence of (recognisable) buried horizons in Anthrosols.

Secondary characteristics qualifiers referring to diagnostic horizons, properties or soil materials

These qualifiers refer to secondary soil characteristics that are directly linked to diagnostic horizons, properties or soil materials but do not indicate an intergrade between Reference Soil Groups.

Qualifier	*Directly related diagnostic horizon, property or soil material*	*Qualifier*	*Directly related diagnostic horizon, property or soil material*	*Qualifier*	*Directly related diagnostic horizon, property or soil material*
Fibric, Folic, Sapric	organic soil material, folic horizon, Histosols	Gelistagnic, Stagnic, Abruptic	stagnic properties, abrupt textural change, Planosols	Ferric	ferric horizon
Aric, Garbic, Reductic, Spolic, Urbic	Anthropedomorphic materials (in Regosols only), Anthrosols	Greyic	mollic horizon, Phaeozems	Profondic, Lamellic, Cutanic	argic horizon,clay illuviation/skins, Alisols, Acrisols, Luvisols, Lixisols
Thionic	sulfuric horizon or sulfidic soil material, Fluvisols, Gleysols	Pachic, Glossic, Humic	mollic or umbric horizon, Cherno-zems, Phaeozems, Umbrisols	Fragic	fragic horizon
Petrosalic, Hypersalic	salic horizon, Solonchaks	Gypsiric	gypsiric soil material, Gypsisols	Yermic	yermic horizon
Silandic, Aluandic, Fulvic, Tephric	silandic, aluandic, and fulvic horizons, tephric soil material, Andosols	Hyperduric	duric horizon, Durisols	Takyric	takyric horizon
Placic	Podzols	Calcaric	calcaric soil material, Calcisols	Aridic	aridic properties
Geric	geric properties, Ferralsols	Albic	albic horizon, Albeluvisols	Hyper-ochric	ochric horizon

SECONDARY CHARACTERISTICS QUALIFIERS NOT REFERRING TO DIAGNOSTIC HORIZONS, PROPERTIES OR SOIL MATERIALS

These qualifiers refer to a soil characteristic that indicates a particular water regime, soil solution or groundwater chemistry, exchange complex specification, weak soil development or morphological characteristics.

Qualifier	*Characteristic and Reference Soil Group*	*Qualifier*	*Characteristic and Reference Soil Group*	*Qualifier*	*Characteristic and Reference Soil Group*
Ombric, Rheic	water regime, Histosols	Aceric, Carbonatic, Chloridic, Sulphatic	soil solution chemistry, Solonchaks	Siltic	high silt content, Chernozems, Kastanozems, Phaeozems
Toxic, Alcalic	soil solution chemistry, Histo-sols, Gleysols	Acroxic	effective CEC, Andosols	Vermic	earthworm activity, Chernozems, Phaeozems, Regosols
Oxyaquic	water regime, Cryosols	Entic	weak development, Podzols	Arzic	sulphate-rich groundwater, Gypsisols
Anthropic (Regosols)	modification by human activity, Anthrosols	Sodic, Magnesic	ESP, exch. Ca:Mg ratio, Solonetz	Alumic	high Al saturation, Alisols
Skeletic	coarse fragments, Leptosols	Gibbsic, Vetic	gibbsite content, low ECECclay, Ferralsols	Protic	no horizon development, Arenosols
Mazic, Grumic, Mesotrophic	surface structure, base saturation, Vertisols	Ruptic	lithological discontinuity, Planosols	Dystric, Eutric	base saturation, many Reference Soil Groups

Qualifiers referring to soil colour can be added to the qualifiers tabulated above, if applicable. Some examples: *Pellic* (Vertisols), *Rhodic* (Ferralsols, Planosols, Alisols, Nitisols, Acrisols, Luvisols, Lixisols, Cambisols), *Xanthic* (Ferralsols), *Chromic* (Vertisols, Planosols, Kastanozems, Phaeozems, Durisols, Alisols, Acrisols, Luvisols, Lixisols, Cambisols) and *Rubic* (Arenosols).

THE 'HAPLIC' QUALIFIER

The *'haplic'* qualifier can occur in all Reference Soil Groups; it communicates that a soil meets the central concept of its Reference Soil Group and that there are no particular soil features that deserve to be separately mentioned. Sparing use of the 'haplic' qualifier is recommended.

SUGGESTIONS FOR RANKING COMMON QUALIFIERS IN EACH REFERENCE SOIL GROUP

HISTOSOLS	CRYOSOLS	ANTHROSOLS	LEPTOSOLS	VERTISOLS
Glacic	Turbic	Hydragric	Lithic	Thionic
Thionic	Glacic	Irragric	Hyperskeletic	
		Terric	Rendzic	Salic
Cryic	Histic	Plaggic		Natric
Gelic	Lithic	Hortic	Gelic	Gypsic
Salic	Leptic		Vertic	Duric
	Salic	Gleyic	Gleyic	Calcic
Folic	Gleyic	Spodic	Mollic	Alic
Fibric	Andic	Ferralic	Umbric	
Sapric	Natric	Luvic		Gypsiric
	Mollic	Arenic	Humic	Grumic
Ombric	Gypsic	Regic	Gypsiric	Mazic
Rheic	Calcic		Calcaric	Mesotrophic
Alcalic	Umbric	Stagnic	Yermic	Hyposodic
Toxic			Aridic	Eutric
	Thionic	Haplic		
Dystric	Stagnic		Dystric	Pellic
Eutric	Yermic		Eutric	Chromic
	Aridic			
Haplic			Haplic	Haplic
	Oxyaquic			
	Haplic			
FLUVISOLS	SOLONCHAKS	GLEYSOLS	ANDOSOLS	PODZOLS
Thionic	Histic	Thionic	Vitric	Densic
	Gelic		Silandic	Carbic
Histic	Vertic	Histic	Aluandic	Rustic
Gelic	Gleyic	Gelic	Eutrisilic	
Salic	Mollic	Anthraquic	Melanic	Histic
Gleyic	Gypsic	Vertic	Fulvic	Gelic
Mollic	Duric	Endosalic	Hydric	Anthric
Umbric	Calcic	Andic		Gleyic
Arenic		Vitric	Histic	Umbric
	Petrosalic	Plinthic	Leptic	
Tephric	Hypersalic	Mollic	Gleyic	Placic
Stagnic	Stagnic	Gypsic	Mollic	
Humic	Takyric	Calcic	Duric	Skeletic
Gypsiric	Yermic	Umbric	Luvic	Stagnic
Calcaric	Aridic	Arenic	Umbric	Lamellic
Takyric	Hyperochric		Arenic	Fragic
Yermic				Entic
Aridic	Aceric	Tephric	Placic	
	Chloridic	Stagnic	Pachic	Haplic
Skeletic	Sulphatic	Abruptic	Calcaric	
Sodic	Carbonatic	Humic		
	Sodic	Calcaric	Skeletic	
Dystric		Takyric	Acroxic	
Eutric	Haplic		Vetic	
		Alcalic	Sodic	
Haplic		Toxic		
		Sodic	Dystric	
		Alumic	Eutric	
		Dystric		
		Eutric	Haplic	
		Haplic		

To be cont’d

PLINTHOSOLS	FERRALSOLS	SOLONETZ	PLANOSOLS	CHERNOZEMS
Petric Endoduric Alic Acric Umbric Geric Stagnic Abruptic Pachic Glossic Humic Albic Ferric Skeletic Vetic Alumic Endoeutric Haplic	Gibbsic Geric Posic Histic Gleyic Andic Plinthic Mollic Acric Lixic Umbric Arenic Endostagnic Humic Ferric Vetic Alumic Hyperdystric Hypereutric Rhodic Xanthic Haplic	Vertic Salic Gleyic Mollic Alcalic Gypsic Duric Calcic Stagnic Humic Albic Takyric Yermic Aridic Magnesic Haplic	Thionic Histic Gelic Vertic Endosalic Gleyic Plinthic Mollic Gypsic Calcic Alic Luvic Umbric Arenic Geric Calcaric Albic Ferric Alcalic Sodic Alumic Dystric Eutric Rhodic Chromic Haplic	Chernic Vertic Gleyic Calcic Luvic Glossic Siltic Vermic Haplic

KASTANOZEMS	PHAEOZEMS	GYPSISOLS	DURISOLS	CALCISOLS
Anthric Vertic Petrogypsic Gypsic Petrocalcic Calcic Luvic Hyposodic Siltic Chromic Haplic	Chernic Leptic Vertic Gleyic Vitric Andic Luvic Tephric Stagnic Abruptic Greyic Pachic Glossic Calcaric Albic Skeletic Sodic Siltic Vermic Dystric Chromic Haplic	Petric Hypergypsic Leptic Vertic Endosalic Duric Calcic Luvic Takyric Yermic Aridic Hyperochric Skeletic Sodic Arzic Haplic	Petric Leptic Vertic Gypsic Calcic Luvic Arenic Hyperduric Takyric Yermic Aridic Hyperochric Chromic Haplic	Petric Hypercalcic Leptic Vertic Endosalic Gleyic Luvic Takyric Yermic Aridic Hyperochric Skeletic Sodic Haplic

To be cont'd

ALBELUVISOLS	ALISOLS	NITISOLS	ACRISOLS	LUVISOLS
Histic Gleyic Alic Umbric Arenic Gelic Stagnic Abruptic Ferric Fragic Siltic Alumic Endoeutric Haplic	Vertic Gleyic Andic Plinthic Nitic Umbric Arenic Stagnic Abruptic Humic Albic Profondic Lamellic Ferric Skeletic Hyperdystric Rhodic Chromic Haplic	Andic Ferralic Mollic Alic Umbric Humic Vetic Alumic Dystric Eutric Rhodic Haplic	Leptic Gleyic Vitric Andic Plinthic Umbric Arenic Stagnic Abruptic Geric Humic Albic Profondic Lamellic Ferric Hyperochric Skeletic Vetic Alumic Hyperdystric Rhodic Chromic Haplic	Leptic Vertic Gleyic Vitric Andic Calcic Arenic Stagnic Abruptic Albic Profondic Lamellic Cutanic Ferric Hyperochric Skeletic Hyposodic Dystric Rhodic Chromic Haplic
LIXISOLS	UMBRISOLS	CAMBISOLS	ARENOSOLS	REGOSOLS
Leptic Gleyic Vitric Andic Plinthic Calcic Arenic Geric Stagnic Abruptic Humic Albic Profondic Lamellic Ferric Hyperochric Vetic Rhodic Chromic Haplic	Thionic Gelic Anthric Leptic Gleyic Ferralic Arenic Stagnic Humic Albic Skeletic Haplic	Thionic Gelic Leptic Vertic Fluvic Endosalic Gleyic Vitric Andic Plinthic Ferralic Gelistagnic Stagnic Humic Calcaric Gypsiric Takyric Yermic Aridic Hyperochric Skeletic Sodic Dystric Eutric Rhodic Chromic Haplic	Gelic Hyposalic Gleyic Hyperalbic Plinthic Hypoferralic Hypoluvic Tephric Gypsiric Calcaric Albic Lamellic Fragic Yermic Aridic Protic Dystric Eutric Rubic Haplic	Gelic Leptic Hyposalic Gleyic Thaptovitric Thaptoandic Arenic Aric Garbic Reductic Spolic Urbic Tephric Gelistagnic Stagnic Humic Gypsiric Calcaric Takyric Yermic Aridic Hyperochric Anthropic Skeletic Hyposodic Vermic Dystric Eutric Haplic

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