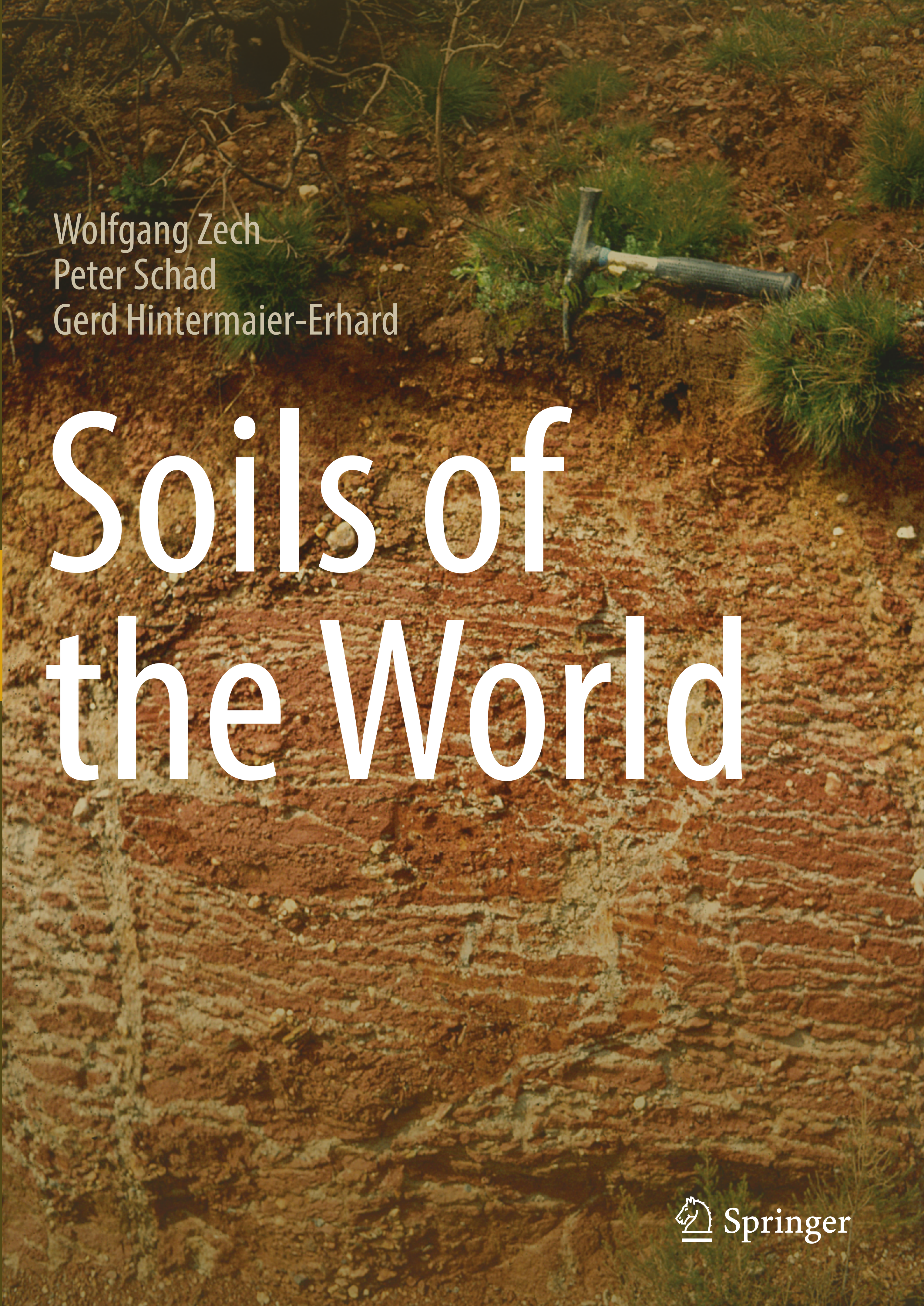
Wolfgang Zech
Peter Schad
Gerd Hintermaier-Erhard

Soils of the World



Springer

Soils of the World

Wolfgang Zech · Peter Schad · Gerd Hintermaier-Erhard

Soils of the World

Springer

Wolfgang Zech
Institute of Soil Science and Soil Geography
University of Bayreuth
Bayreuth, Germany

Peter Schad
Chair of Soil Science
Technical University of Munich
Freising-Weihenstephan, Germany

Gerd Hintermaier-Erhard
Landsberg am Lech, Germany

ISBN 978-3-540-30460-9 ISBN 978-3-540-30461-6 (eBook)
https://doi.org/10.1007/978-3-540-30461-6

Original German edition published by Spektrum Akademischer Verlag GmbH Heidelberg, 2002
Translated from the German language edition: Böden der Welt by the authors © Elsevier GmbH, Spektrum Akademischer Verlag 2002. Published by Elsevier GmbH, Spektrum Akademischer Verlag. All Rights Reserved.

Cover photo: Stagnic Plinthosol from Spain (see Fig. 10.7.b)

Responsible Editor: Christian Witschel (Johannes Botschek and Martin Hamer provided advices, based on the first edition of the German textbook Böden der Welt)
This Springer imprint is published by the registered company Springer-Verlag GmbH, DE part of Springer Nature.
The registered company address is: Heidelberger Platz 3, 14197 Berlin, Germany

Preface

This book is based on the German textbook *Böden der Welt* (first edition 2002 by Spektrum Akademischer Verlag, Heidelberg; second edition 2014 by Springer-Spektrum, Heidelberg). It is not only a translation of the German book but takes into account the fast development and new insights in soil science since 2014. The soils of our planet are presented by more than 260 photographs and described according to the World Reference Base for Soil Resources (WRB), a soil classification system of the International Union of Soil Sciences (IUSS Working Group WRB, third edition 2014, update 2015). This system fosters our understanding of soil genesis, distribution, fertility and resilience. The graphics of the first edition of the German book were largely developed and implemented by Gerd Hintermaier-Erhard. Those of the second German edition were drawn by Elfriede Schuhbauer and then adapted and further elaborated for the English edition by Peter Schad.

Soils are the key factor of food production for the increasing population. Soil carbon stocks play a major role in the global carbon cycle and thus significantly control the climate. We hope that our book fascinates the reader about the beauty and importance of this precious natural resource and thus contributes to a better understanding of the pedosphere.

While the German textbook (2002) was established by Wolfgang Zech and his student Gerd Hintermaier, the main author of the English edition (2022) is Peter Schad.

Wolfgang Zech
Peter Schad
Gerd Hintermaier-Erhard
Autumn 2021

Contents

Abbreviations

a — year(s)

AC — air capacity: volume of the coarse pores with rapid water drainage; > 50 µm equivalent diameter; pF < 1.8; given in mm dm^{-1} (or %) or in mm of the effective rooting depth

AEC — anion exchange capacity in $cmol_c\ kg^{-1}$ FE

Al_{dith} — aluminium, extractable in a solution of Na dithionite bicarbonate citrate (DBC)

Al_{ox} — aluminium, extractable in a solution of acid NH_4 oxalate

Al_{py} — aluminium, extractable in a solution of Na pyrophosphate

BS — base saturation in %; two types:

$$BS_{pot} = [(Ca^{2+} + Mg^{2+} + K^{+} + Na^{+})/CEC_{pot}] \times 100$$

$$BS_{eff} = [(Ca^{2+} + Mg^{2+} + K^{+} + Na^{+})/CEC_{eff}] \times 100$$

cal ka BP — calibrated kiloyears before present (present: 1950 AD)

CEC_{pot} — potential cation exchange capacity (pH buffered to 7) in $cmol_c\ kg^{-1}$ FE or kg^{-1} clay

CEC_{eff} — effective cation exchange capacity (pH of the soil, unbuffered) in $cmol_c\ kg^{-1}$ FE or kg^{-1} clay (sum of exchangeable Ca^{2+}, Mg^{2+}, K^+, Na^+ and Al^{3+})

cmol — centimol

$cmol_c$ — centimol charge

C_{org} — organic C

$\delta^{13}C$ — $[(R_{sample}/R_{standard}) - 1] \times 1000$, with $R = {}^{13}C/{}^{12}C$; carbon reference standard = VPDB (Vienna pee Dee belemnite)

$\delta^{18}O$ — like $\delta^{13}C$, with $R = {}^{18}O/{}^{16}O$; oxygen reference standard = VSMOW (Vienna Standard Mean Ocean Water)

d — day

DOM — dissolved organic matter

EC — electrical conductivity

EC_e — electrical conductivity in the saturation extract

ESP — exchangeable sodium percentage

ET — evapotranspiration

exch — exchangeable

FE — fine earth, particles ≤ 2 mm

Fe_{dith} — iron, extractable in a solution of Na dithionite bicarbonate citrate (DBC) ('free' or pedogenic iron)

Fe_{ox} — iron, extractable in a solution of acid NH_4 oxalate (poorly crystallized pedogenic iron)

h — hour

HACs — high activity clays (2:1 clay minerals, with high CEC)

HM — heavy metal

ka — kiloyear(s)

LACs — low activity clays (clay minerals with low CEC, mostly 1:1 clay minerals like kaolinite)

LGM — Last Glacial Maximum (ca. 26–19 ka BP)

MAOM — mineral-associated organic matter

MAP — Mean Annual Precipitation

MAT — Mean Annual Temperature

min — mineral

NPP — net primary production

OC — organic carbon (C_{org})

OM — organic matter (roughly: $C_{org} \times 2$)

org — organic

P — precipitation

PAWC — plant-available water capacity (plant-available field capacity): volume of the medium-sized pores + the coarse pores with slow water drainage; 0.2–50 µm equivalent diameter; pF 1.8–4.2; given in mm dm^{-1} (or %) or in mm of the effective rooting depth

Pg — petagram (10^{15} g)

PV — pore volume

rH — negative logarithm (base 10) of the hydrogen partial pressure

RSG — Reference Soil Group

SAR — sodium adsorption ratio: $Na^+/0.5\ (Ca^{2+} + Mg^{2+})^{0.5}$; ions given in $mmol_c\ liter^{-1}$

SOC — soil organic carbon (C_{org})

SOM — soil organic matter

Si_{ox} — silicon, extractable in a solution of acid NH_4 oxalate

TRB — total reserve of bases (exchangeable + mineral Ca, Mg, K and Na)

WC water capacity (field capacity): plant-available water + not available water; water in fine pores + medium-sized pores + coarse pores with slow water drainage; ≤ 50 µm equivalent diameter; pF ≥ 1.8; given in mm dm^{-1} (or %) or in mm of the effective rooting depth

WRB World Reference Base for Soil Resources

Introduction

Contents

W. Zech et al., *Soils of the World*,
https://doi.org/10.1007/978-3-540-30461-6_1

1.1 The World Reference Base for Soil Resources (WRB)

The WRB is an international soil classification system. It is edited by the Working Group WRB of the International Union of Soil Sciences (IUSS). The third edition 2014, update 2015, is the currently valid version (IUSS Working Group WRB, 2015). The first edition stems from 1998 (FAO, 1998) and the second from 2006 (IUSS Working Group WRB, 2006). The WRB has its roots in the Soil Map of the World, the respective Legend (FAO/UNESCO, 1974) and the Revised Legend (FAO, 1988).

WRB has two levels of hierarchy. The First Level comprises 32 **Reference Soil Groups (RSGs)**, which are identified using a key (▶ Chap. 4 of the WRB manual). In the Second Level, the soil names are constructed by combining the name of the RSG with adjectives, called **qualifiers**. WRB defines 185 qualifiers (▶ Chap. 5 of the WRB manual). Some qualifiers can be combined with many RSGs, others only with a few ones or with just one.

For every RSG, there is an individual list of available qualifiers (▶ Chap. 4 of the WRB manual, along with the key). In this list, the qualifiers are subdivided into **principal and supplementary qualifiers**. Principal qualifiers are ranked and listed according to their importance. Supplementary qualifiers are not ranked and listed in alphabetical order. Some qualifiers may be principal for some RSGs and supplementary for others. The Cambisols have the longest list with 68 available qualifiers. Nitisols and Gypsisols have the shortest lists with 35 available qualifiers, each. Many qualifiers are mutually exclusive. If in a list, two or more qualifiers are separated by a slash (/) only one of them can be used. The slash signifies that these qualifiers are either mutually exclusive (e.g. Dystric and Eutric) or one of them is redundant (e.g. Mollic does not add information if the Rendzic qualifier applies) with the redundant qualifier(s) listed after the slash(es). In the soil name, supplementary qualifiers are always placed in the order of the alphabet, even if their position in the list differs from alphabetical sequence due to the use of the slash.

For naming a soil, check the lists of the available qualifiers and add all that apply. Principal qualifiers are added before the name of the RSG from right to left (the uppermost qualifier in the list is placed closest to the name of the RSG). Supplementary qualifiers are added after the name of the RSG from left to right, in brackets and separated from each other by commas (the first qualifier according to the alphabet is placed closest to the name of the RSG).

Qualifiers may be combined with **specifiers** (e.g. Epi-, Proto-) to form **subqualifiers** (e.g. Epiarenic, Protocalcic) for a more specific characterization of the soil. Widely used are specifiers referring to depth requirements (see WRB manual). The alphabetical sequence of the supplementary qualifiers is according to the qualifier, not the specifier. Only if the Bathy- (very deep) or the Thapto- (buried, see below) specifier is used, the subqualifier is added in the soil name at the end of the set of supplementary qualifiers.

The definitions of the RSGs (▶ Chap. 4 of the WRB manual) and of the qualifiers (▶ Chap. 5 of the WRB manual) are based on diagnostic horizons, diagnostic properties and diagnostic materials (defined in ▶ Chap. 3 of the WRB manual), together called **diagnostics**. The criteria of the diagnostics may be field and laboratory characteristics. The key and the definitions of the qualifiers ask for the presence or absence (at a certain depth) of certain diagnostics. In addition, they ask for the presence or absence of single characteristics (e.g. a certain clay content or a certain base saturation). **Diagnostic materials** are materials that significantly influence soil-forming processes; they may stem from the parent material or be the result of soil-forming processes. **Diagnostic properties** are typical results of soil-forming processes or reflect specific conditions of soil formation. **Diagnostic horizons** are also typical results of soil-forming processes but with a minimum thickness and therefore recognizable as horizontal layer. Not all the horizons found in a soil profile form part of a diagnostic horizon.

WRB has established rules for classifying **buried soils**. A buried soil is a soil covered by younger deposits. Where a soil is buried, the following rules apply:

The overlying material and the buried soil are classified as one soil if both together qualify as a Histosol, Anthrosol, Technosol, Cryosol, Leptosol, Vertisol, Gleysol, Andosol, Planosol, Stagnosol, Arenosol, Fluvisol or Regosol.

Otherwise, the overlying material is classified with preference if it is ≥ 50 cm thick or if the overlying material, if it stood alone, satisfies the requirements of a Folic Regosol or of a RSG other than a Regosol. For depth requirements in the overlying material, the lower limit of the overlying material is regarded as if it were the upper limit of *continuous rock*.

In all other cases, the buried soil is classified with preference. For depth requirements in the buried soil, the upper limit of the buried soil is regarded as its soil surface.

If the overlying soil is classified with preference, the name of the buried soil is placed after the name of the overlying soil adding the word 'over' in between, e.g. Skeletic Umbrisol (Siltic) over Albic Podzol (Arenic). This is preferred if the buried soil has a full horizon sequence, including a well-developed A horizon. Alternatively, instead of the buried soil, a qualifier indicating a buried diagnostic horizon or a buried layer with a diagnostic property can be added with the Thapto- specifier to the name of the overlying soil (e.g. Eutric Cambisol (Thaptomollic)).

If the buried soil is classified with preference, the overlying material is indicated with the Novic qualifier and, if applicable, with the qualifiers Aeolic, Akrofluvic, Colluvic or Transportic (e.g. Haplic Phaeozem (Novic)).

WRB can also be used for creating map legends. In this case, the rule to add all applying qualifiers to the soil name is not valid. Instead, the number of qualifiers is restricted according to the scale level (see WRB manual). For further explanations about the use of the WRB, see Schad & Dondeyne (2017).

In this book, the diagnostics, mentioned in the text, are given in *italics* (in headlines also in **bold**). Qualifiers, if used without a RSG, are marked with an asterisk*. For every RSG, the full list of available qualifiers is provided.

1.2 Horizon Designations

This book uses the horizon designations of the FAO Guidelines for Soil Description (FAO, 2006). Master horizons and layers are indicated by capital letters and presented in ◘ Table 1.1 (some of the definitions modified).

The lowercase letters shown in ◘ Table 1.2 are used as suffixes to designate specific kinds of the master horizons or layers (R, I and W cannot have suffixes; some of the definitions modified).

For transitional horizons, the symbols are combined. If properties of two horizons are intimately mixed, the symbols are combined directly, e.g., AhBw. If in one horizon distinct parts have properties of two different horizons, they are combined using a slash, e.g., Bt/E. The first symbol is always the dominating one. In case of *lithic discontinuities*, for the second stratum the numeral 2, for the third the numeral 3 etc. is added before every horizon symbol. In the horizon sequence of a soil profile, the horizons are separated from each other by hyphens, e.g., Ah-E-2Bt-2C. Two or more horizons with identical designation are indicated by numerals at the end, e.g., Ah1-Ah2.

◘ **Table 1.1** Master horizon symbols

Symbol	Description
H	Organic material accumulated under prolonged water saturation
O	Organic material accumulated without prolonged water saturation
A	Mineral horizon formed at the mineral soil surface in which all or much of the original rock structure is lost and with one or more of the following: – Accumulation of microbially altered organic matter or – Properties resulting from land use or – A morphology different from underlying B or C horizons
E	Mineral horizon that has lost organic matter, clay minerals, iron and/or aluminium and in which all or much of the original rock structure is lost
B	Mineral horizon formed in the subsoil in which all or much of the original rock structure is lost and with one or more of the following: – Evidence of alteration that formed clay minerals and/or oxides or – Evidence of removal of carbonates or – Residual accumulation of oxides or – Illuvial accumulation of clay minerals, iron, aluminium, OM, carbonates, gypsum and/or silica or – Coatings of oxides that make the horizon lower in value, higher in chroma and/or redder in hue or – Brittleness
C	Unconsolidated mineral horizon or layer, little affected or unaffected by pedogenic processes, may be altered by processes not related to the soil surface, may be chemically weathered and/or have accumulation of carbonates, gypsum and/or silica if the original rock structure is more or less preserved
R	Hard bedrock
I	≥ 75% (by volume) ice
L	Limnic material (organic or mineral), deposited in a body of water
W	Water layer, permanent or cycling within the time frame of 24 h

1.3 Particle Sizes and Texture

This book uses the particle-size classes of the ISO and the texture classes of the Soil Survey Manual of the United States Department of Agriculture (Soil Science Division Staff, 2017). Table 1.3 defines the particle-size classes. Figure 1.1 and Table 1.4 define the texture classes. The colours indicate the textural qualifiers of the WRB.

Table 1.2 Horizon suffixes

Suffix	Description	Used for
a	Highly microbially altered organic material	H, O
b	Buried genetic horizon	Mineral horizons, not cryoturbated
c	Concretions or nodules	Mineral horizons
c	Coprogenous earth	L
d	Dense layer (physically root-restrictive)	Mineral horizons, not strongly cemented (without …m)
d	Diatomaceous earth	L
e	Moderately microbially altered organic material	H, O
f	Frozen soil	No restriction
g	Redoximorphic features due to stagnant water	No restriction
h	Accumulation of organic matter	Mineral horizons
i	Slickensides	Mineral horizons
i	Slightly microbially altered organic material	H, O
j	Jarosite accumulation	No restriction
k	Accumulation of pedogenic carbonates	No restriction
l	Redoximorphic features due to ascending groundwater	No restriction
m	Strong cementation (pedogenic, massive)	Mineral horizons
m	Marl	L
n	Pedogenic accumulation of exchangeable sodium	No restriction
o	Residual accumulation of oxides (pedogenic)	Mineral horizons
p	Ploughing	O, H, A (E, B, C are named A after disturbance)
q	Accumulation of pedogenic silica	Mineral horizons
r	Reducing conditions almost year-round	No restriction
s	Illuvial accumulation of oxides	B
t	Illuvial accumulation of clay minerals	B, C
u	Significant amendments of urban and other human-made materials	No restriction
v	Occurrence of plinthite	Mineral horizons
w	Pedogenic development of colour and/or structure	B
x	Fragipan characteristics	Mineral horizons
y	Pedogenic accumulation of gypsum	No restriction
z	Accumulation of salts more soluble than gypsum	No restriction
@	Evidence of cryoturbation	No restriction

Table 1.3 Particle-size classes

Particle-size class	Diameter of particles
Coarse fragments	All particles > 2 mm
Fine earth	All particles ≤ 2 mm
Sand	> 63 µm - ≤ 2 mm
Very coarse sand	> 1250 µm - ≤ 2 mm
Coarse sand	> 630 µm - ≤ 1250 µm
Medium sand	> 200 µm - ≤ 630 µm
Fine sand	> 125 µm - ≤ 200 µm
Very fine sand	> 63 µm - ≤ 125 µm
Silt	> 2 µm - ≤ 63 µm
Clay	≤ 2 µm

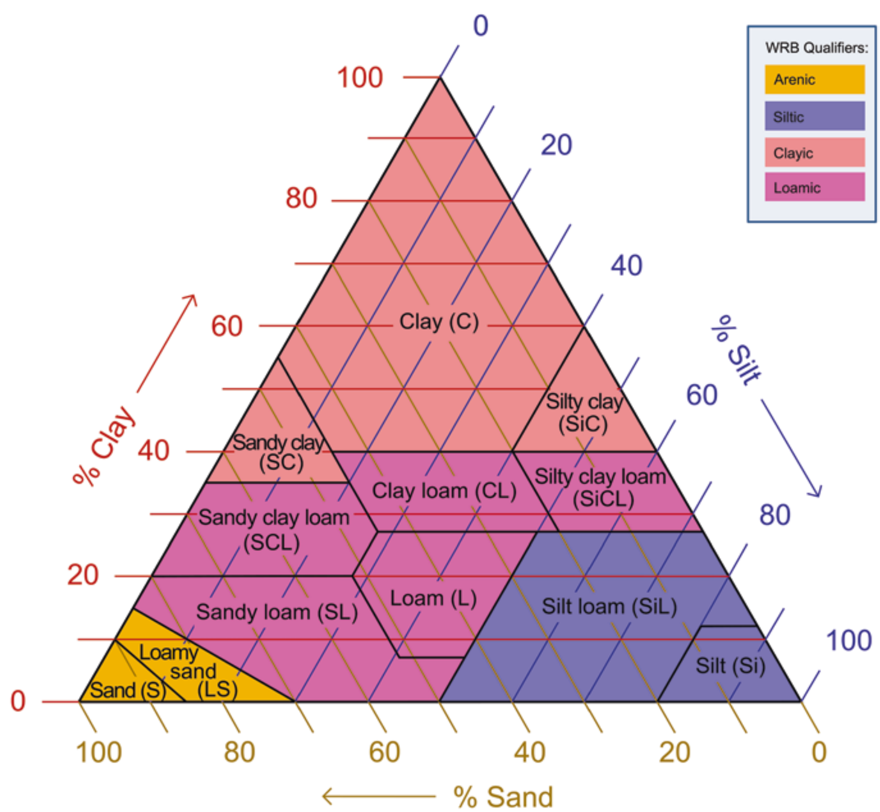


Fig. 1.1 Texture triangle, courtesy of V. Buness, modified after Soil Science Division Staff (2017) and Blum et al. (2018)

Table 1.4 Texture classes

Texture class	% sand	% silt	% clay	Additional criteria
Sand (S)	> 85	< 15	< 10	(%silt + 1.5×%clay) < 15
Loamy sand (LS)	> 70 to ≤ 90	< 30	< 15	(%silt + 1.5×%clay) ≥ 15 and (%silt + 2×%clay) < 30
Silt (Si)	≤ 20	≥ 80	< 12	
Silt loam (SiL)	≤ 50	≥ 50 to < 80	< 27	
	≤ 8	≥ 80 to ≤ 88	≥ 12 to ≤ 20	
Sandy loam (SL)	> 52 to ≤ 85	≤ 48	< 20	(%silt + 2×%clay) ≥ 30
	> 43 to ≤ 52	≥ 41 to < 50	< 7	
Loam (L)	> 23 to ≤ 52	≥ 28 to < 50	≥ 7 to < 27	
Sandy clay loam (SCL)	> 45 to ≤ 80	< 28	≥ 20 to < 35	
Silty clay loam (SiCL)	≤ 20	> 40 to ≤ 73	≥ 27 to < 40	
Clay loam (CL)	> 20 to ≤ 45	> 15 to < 53	≥ 27 to < 40	
Sandy clay (SC)	> 45 to ≤ 65	< 20	≥ 35 to < 55	
Silty clay (SiC)	≤ 20	≥ 40 to ≤ 60	≥ 40 to ≤ 60	
Clay (C)	≤ 45	< 40	≥ 40	

1

1.4 Overview of the Reference Soil Groups and Their Distribution across the Ecozones

In this book, the soils of the 32 Reference Soil Groups (RSGs) of the WRB are presented in eleven chapters. Nine chapters refer to an ecozone and describe the RSGs that have their major occurrence in the respective ecozone. The other chapters describe 'Ubiquitous soils' and the soils of 'Mountain regions'. The division of the biosphere into nine ecozones follows the concept of Schultz (2000, 2005, 2016). Each chapter starts with short paragraphs about location, climate and vegetation. Of course, none of the soils is restricted to just one ecozone. Table 1.5 shows the RSGs with typical horizon sequences, a brief description and their major occurrence with respect to the ecozones.

Table 1.5 The Reference Soil Groups with typical horizon sequences, a brief description and their major occurrence with respect to the ecozones

Reference Soil Group	Typical horizon sequences	Brief description	Major occurrence (explanation below)
Acrisol	Ah-E-Bt-C, Ah-Bt-C	Soils with pedogenic clay accumulation in the subsoil, dominated by LACs (CEC_{pot} <24 $cmol_c$ kg^{-1} clay); low BS_{eff} (< 50%) in the subsoil	**7,** 9, 10
Alisol	Ah-E-Bt-C, Ah-Bt-C	Soils with pedogenic clay accumulation in the subsoil, dominated by HACs (CEC_{pot} ≥24 $cmol_c$ kg^{-1} clay); low BS_{eff} (< 50%) in the subsoil	4, **7**
Andosol	Ah-C, Ah-Bw-C	Soils developed from glass-rich parent material, especially pyroclasts (in places: from other silicate-rich parent material)	(3, 4, 5, 6, 7, 8, 9, 10), **11**
Anthrosol	Ap-Ah-2Bw-2C, Arp-Ardp-Bg-C	Soils strongly altered by long-term human influence, especially by agriculture	**12**
Arenosol	A-C, Ah-C	Sandy soils with little profile differentiation	5, **8,** 9, 10
Calcisol	A-Ck, A-Bk-Ck, Ah-Bk-C, Ah-Bkc-C, Ah-Bkm-C	Soils with accumulation of pedogenic carbonates	5, 6, **8,** (11)
Cambisol	Ah-Bw-C	Soils having a subsoil horizon that is at least weakly developed but lacks the characteristics of advanced soil formation	(2, 3), **4,** (5), **6,** (7), **8,** (9), 11
Chernozem	Ah-Ck, Ah-Bw-Ck, Ah-E-Btk-Ck, Ah-Btk-Ck	Soils with Ah horizons that are thick, blackish, well-structured and rich in OM; pedogenic carbonates present; high BS throughout	4, **5,** (11)
Cryosol	Ah@-Bw@-Cf, Ah-Bwf-Cf	Soils with permafrost within 100 cm, or within 200 cm if cryoturbation features are present in the upper 100 cm; mineral material predominates	**2, 3,** 11
Durisol	A-Bqc-C, Ah-Bqc-C, A-Bw-Bqc-C, A-Bw-Bqm-C	Soils with accumulation of pedogenic silica	(5), **8**
Ferralsol	Ah-Bo-C	Strongly weathered soils, dominated by kaolinites and oxides; CEC_{pot} <16 $cmol_c$ kg^{-1} clay; stable microstructure	7, 9, **10**
Fluvisol	Ah-C, Ah-2C-3Ah-3C	Soils developed from alluvial sediments with obvious stratification	**12**
Gleysol	Ah-Bl-Cr, Ahl-Br-Cr, Ah-Bl-C, H-Br-Cr	Soils affected by groundwater at shallow depth	2, **3,** 4, 7, 10, (11)
Gypsisol	Ay-Cy, A-By-Cy, Ah-By-C, Ah-Bym-C	Soils with accumulation of pedogenic gypsum	5, 6, **8**
Histosol	H-Cr, H@-Hf-Cf, O-R	Soils with thick layers of organic material, including organic permafrost soils	2, **3,** 4, 10, 11

Table 1.5 (continued)

Reference Soil Group	Typical horizon sequences	Brief description	Major occurrence (explanation below)
Kasta-nozem	Ah-Ck, Ah-Bk-Ck, Ah-E-Btk-Ck, Ah-Btk-Ck	Soils with Ah horizons that are thick, dark and rich in OM; pedogenic carbonates present; high BS throughout	**5,** (6, 8), 11
Leptosol	O-Ah-Bw-C, Ah-C, Ah-Bw-R, O-Ah-R	Shallow soils or soils with high amounts of coarse fragments; little fine earth	2, 3, (4, 5), 6, (7), **8,** (9), **11**
Lixisol	Ah-E-Bt-C, Ah-Bt-C	Soils with pedogenic clay accumulation in the subsoil, dominated by LACs (CEC_{pot} <24 $cmol_c$ kg^{-1} clay); high BS_{eff} (≥ 50%) in the subsoil	6, (7), **9,** (10)
Luvisol	Ah-E-Bt-C, Ah-Bt-C	Soils with pedogenic clay accumulation in the subsoil, dominated by HACs (CEC_{pot} ≥24 $cmol_c$ kg^{-1} clay); high BS_{eff} (≥ 50%) in the subsoil	(3), **4,** 5, **6,** (7), 8, (9, 11)
Nitisol	Ah-Bo-C, Ah-E-Bto-C	Soils with high amounts of clay minerals and Fe oxides; in the subsoil strong aggregates with shiny surfaces	7, **9,** 10
Phaeozem	Ah-C, Ah-Bw-C, Ah-E-Bt-C	Soils with Ah horizons that are thick, dark and rich in OM; no pedogenic carbonates present (unless in greater depths); high BS throughout	(3), 4, **5,** 7, (10, 11)
Planosol	Ah-Eg-2Bwg-2C, Ah-Eg-Btg-C	Soils with stagnant water during some time of the year; distinct texture difference between coarser topsoil and finer subsoil	3, 4, 5, (6, 7), **9**
Plinthosol	Ah-Eg-Bvg-C, Ah-Bv-C, Ah-Bvc-C, Ah-Bvm-C	Soils with plinthite (soft), pisoliths (hard concretions) or petroplinthite (massively hard), rich in kaolinite	7, **9, 10**
Podzol	O-A-E-Bhs-Bs-C	Acidic soils with migration of Al, Fe and OM from the topsoil into the subsoil	**3,** 4, (7), 10, **11**
Regosol	A-C, Ah-C	Soils with little profile differentiation, mostly developed from silty or clayey parent materials	2, (3, 4, 5, 6, 7), **8,** (9), **11**
Retisol	Ah-E-Bt/E-Bt-C, Ah-Bt/E-Bt-C	Soils with pedogenic clay accumulation in the subsoil; eluvial and illuvial horizons interfingering	**3,** 4
Solonchak	Az-Cz, Ahz-Cz, Ah-Bz-C	Soils with accumulation of readily soluble salts	(2), 5, (6), **8**
Solonetz	Ah-E-Btn-C, Ah-Btn-C	Soils with pedogenic clay accumulation in the subsoil; high Na saturation	(3), **5,** (6), **8**
Stagnosol	Ah-Bg-C, Ah-Eg-Btg-C	Soils with stagnant water during some time of the year; little or no texture difference between topsoil and subsoil	(2), **3, 4,** (7, 10), 11
Technosol	Ah-2Cu, Ahl-2Our, Ru-2C-3Bw-3C	Soils with a significant amount of materials made or significantly altered by humans or brought to the surface from greater depths	**12**
Umbrisol	Ah-Bw-C, Ah-C	Soils with Ah horizons that are thick, dark and rich in OM; low BS at least somewhere within 1 m	3, **4,** (7), 10, **11**
Vertisol	Ah-Bw-Bi-C, Ah-Bi-C	Clay-rich soils with pronounced shrink/swell dynamics	(5, 6), **9**

Explanations:
(The figures coincide with the numbers of the chapters of this book.)

2 – Polar-subpolar zone (tundra zone)
3 – Boreal zone (taiga zone)
4 – Humid mid-latitudes
5 – Dry mid-latitudes
6 – Subtropics with winter rain
7 – Subtropics with year-round rain
8 – Dry tropics and subtropics
9 – Tropics with summer rain
10 – Tropics with year-round rain
11 – Mountain regions
12 – Ubiquitous soils

Extent of Occurrence:
2 – (co-)dominant

2 – common

(2) – minor, typically in border areas to neighbouring ecozones

References

Blum, W. E. H., Schad, P., & Nortcliff, S. (2018). *Essentials of soil science*. Borntraeger Science Publishers.

FAO-UNESCO. (1974). *Soil map of the world, 1 : 5 000 000. Volume 1, Legend.* UNESCO.

FAO. (1988). *Soil map of the world. Revised legend.* By: FAO-UNESCO-ISRIC. World Soil Resources Reports 60. FAO.

FAO. (1998). *World reference base for soil resources*. By: ISSS-ISRIC-FAO. World Soil Resources Reports 84. FAO.

FAO. (2006). *Guidelines for soil description* (4th ed.). Prepared by: R. Jahn, H.-P. Blume, V.B. Asio, O.C. Spaargaren, & P. Schad. FAO.

IUSS Working Group WRB. (2006). *World reference base for soil resources 2006*. World Soil Resources Reports 103. FAO.

IUSS Working Group WRB. (2015). *World reference base for soil resources 2014, update 2015*. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports 106. FAO.

Schad, P., & Dondeyne, S. (2017). World reference base for soil resources. In: Lal, R. (Ed.), *Encyclopedia of soil science* (3rd ed.), 2650–2653. Taylor & Francis. DOI: 10.1081/E-ESS3-120053850.

Schultz, J. (2000). *Handbuch der Ökozonen*. Ulmer.

Schultz, J. (2005). *The ecozones of the world*. Springer.

Schultz, J. (2016). *Die Ökozonen der Erde* (5th ed.). Ulmer.

Soil Science Division Staff. (2017). *Soil survey manual.* US Department of Agriculture Handbook No. 18.

Polar-Subpolar Zone (Tundra Zone)

Contents

W. Zech et al., *Soils of the World*,
https://doi.org/10.1007/978-3-540-30461-6_2

2.1 Location, Climate and Vegetation

Location

The polar-subpolar zone comprises the cold deserts with a lot of frost debris, which are snow- and ice-free in summer, and, towards lower latitudes, the treeless tundra. In the Northern Hemisphere, its southern border roughly equals – except in mountain regions – the 10 °C-July isotherm. Main extensions are:

- **Northern Hemisphere:** Northern rims of Alaska, Canada, Scandinavia and Russia; coasts of Greenland, parts of Iceland.
- **Southern Hemisphere:** the coastlines of Antarctica.

In many high mountains, like Tian Shan, Altai and Sayan Mountains, below the snowline plant communities are found that are typical for the polar-subpolar zone. In Russian literature this area is often called 'mountain tundra'; downslope follows the so-called 'mountain taiga'.

Climate

Pronounced seasonal climate, daily variations in temperature are negligible compared to annual variations. Crucial is the semi-annual change from polar winter to polar summer.

Climate is of (sub)polar type (E, ET, partly DF, according to Köppen & Geiger, 1954). During the warmest month temperatures rise to +6…10 °C, the three warmest months would be on average above +5 °C, the four warmest above 0 °C; annual mean is below 0 °C. Snow cover can last up to 300 d a^{-1}.

Vegetation

The plant cover is a tundra vegetation with dwarf shrubs (chamaephytes), grasses and smaller herbs (mainly hemicryptophytes). These plants show a low optimum in photosynthesis, and both vegetative (runners) as well as generative (seeds) reproduction are common. Such double strategies are characteristic for harsh environmental conditions. In the Northern Hemisphere, from N to S, the following vegetation belts exist (Pfadenhauer & Klötzli, 2020):

- **Polar desert:** Nearly without plant cover.
- **High arctic moss and lichen tundra:** Mainly with little or no plant cover. Solifluction covers and slope debris are common. Mosses and lichens dominate.
- **Middle arctic grass, dwarf and prostrate shrub tundra:** Patches without plant cover alternate with patches of sedges, dwarf shrubs, prostrate shrubs (e.g. *Salix arctica*), mosses and lichens.
- **Low arctic small and dwarf shrub tundra:** Closed plant cover including shrub willows, shrub birches, dwarf shrubs, mosses, lichens.
- **Forest tundra:** Transition zone between low arctic tundra and boreal forest (taiga). The plant cover is a mosaic of forest patches, open woodland and shrub tundra. Near the sea (e.g. Scandinavia, Kamchatka) birches are common; otherwise conifers (spruce, pine, larch) dominate.

The growing season is confined to 2–3 months (June–September).

2.2 Soil Formation and Distribution

Soil Formation

Soil formation is essentially influenced by the semi-annual change of freezing and thawing. Frost weathering, especially in frost debris areas, is the most important process.

Probably since the Middle Pleistocene, large areas of the tundra and also the taiga are deeply frozen by continuous **permafrost** (which differs from discontinuous and sporadic permafrost). Permafrost occupies about 20 to 25% of the earth's surface and can reach depths up to 1500 m in Siberia and up to 20 m in Scandinavia. The upper part (some cm to a few meters) is melting during the short summer and refreezes in the winter months. It is called the 'active layer'. This cycle is accompanied by solifluction and cryoturbation (▣ Fig. 2.1), including frost heave, formation of ice wedges and material sorting (patterned ground, e.g., stone rings, stone stripes etc.).

Despite low biomass production, there is a substantial enrichment of organic matter in the tundra, because decomposition is inhibited due to low temperatures and water saturation.

Soil Distribution

The dominant soil in the polar-subpolar zone is the **Cryosol**, for which the *cryic horizo*n is diagnostic. Cryosols are composed of mineral soil material but may also have thin organic layers. Many of the Cryosols have layers of massive ice. The *cryic horizon* is frozen all the year (permafrost) and has soil temperatures of 0 °C or (far) below. Cryosols are common especially in regions with continuous permafrost.

Where *organic material* (typically peat) is accumulated, **Histosols** may form. In warmer areas, even Chernozems were described besides **Cryosols** (Chimitdorzhieva et al., 2019). If many *artefacts* are present in the soil, for instance in areas of oil production, coal or ore mining, **Technosols** may be found. Histosols as well as Technosols can show all the typical features of Cryosols.

The following soils partially lack the Cryosol features: **Leptosols** are common in the stone- and debris-rich (sub)polar desert and tundra regions or on

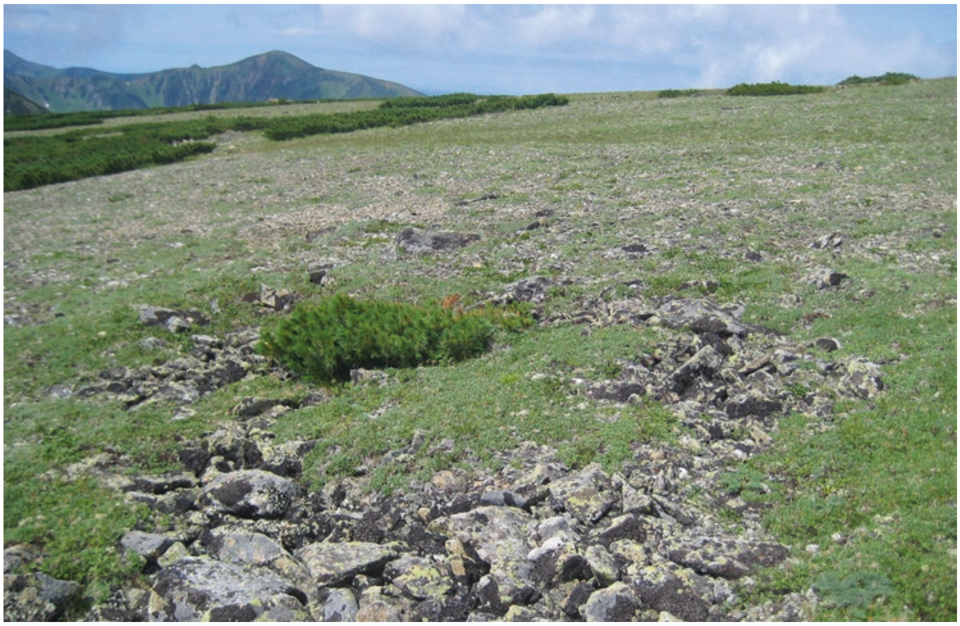


Fig. 2.1 **The tundra's mostly 'smooth' landforms** are shaped by the frequently occurring frost-thaw cycles, which give rise to soil creep and material sorting. The soils are mainly shallow and their thickness changes according to the frost-controlled micro-relief. The vegetation is adapted to these particular site conditions and shows a variation of grasses, mosses, lichens, dwarf shrubs (<0.5 m) and small shrubs (0.5–1.5 m)

continuous rock. Initial processes of soil formation on fine-grained surface layers, e.g., till (from ground moraines), periglacial layers, solifluction deposits and fine-earth patches give rise to **Regosols**. On well-drained sites, they may be developed into **Cambisols** due to progressive weathering and the formation of Fe oxides and clay minerals.

On sites with poor drainage (e.g. above deep permafrost), **Stagnosols** are common, and in depressions with high groundwater levels, **Gleysols** will develop, showing increased organic matter accumulation in the topsoils. In drier areas, the accumulation of readily soluble salts allows the formation of **Solonchaks** that need temperatures markedly below 0 °C for freezing and that occur, e.g., at Antarctica's coasts, From there, also **Podzols**, **Arenosols** and **Andosols** have been reported.

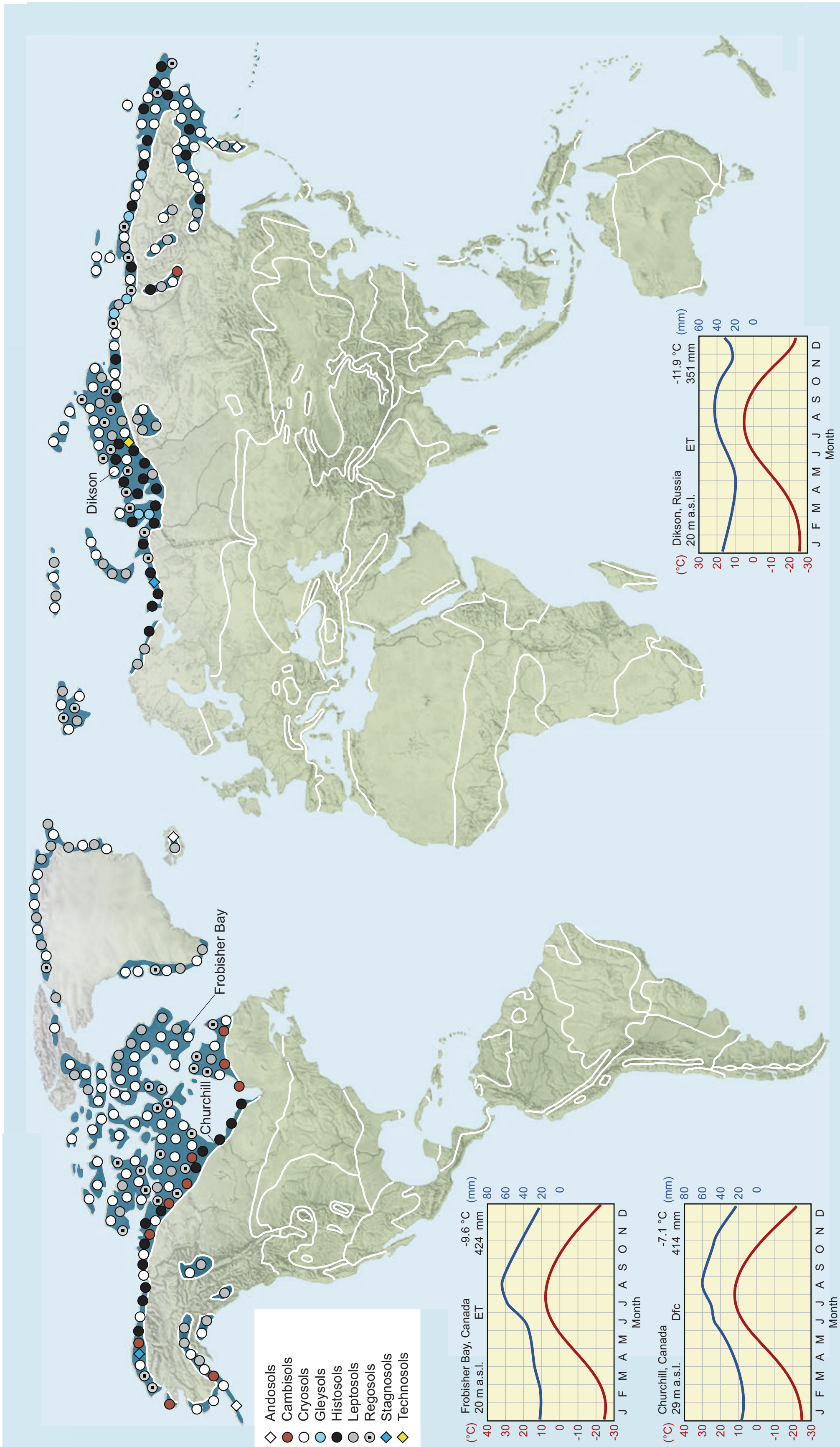
Cryosols and other typical soils of the polar-subpolar zone are also found in cold high mountain areas ('mountain tundra'). Figure 2.2 shows the distribution of the RSGs in the Northern Hemisphere.

Carbon Dynamics and Its Importance for Permafrost Soils

Due to increasing climate warming, an enhanced thawing of permafrost soils is expected, which will lead to an accelerated mineralization and to the release of greenhouse gases like CH_4, CO_2 and N_2O from tundra and taiga soils (Rodionov et al., 2006).

Compared to interglacial periods, during Pleistocene glacial periods more carbon has been stored in permafrost soils, although biomass production was significantly lower (Zech, 2012; Zech et al., 2011). Today, total organic carbon in the northern permafrost soils amounts to ca. 1700 Pg (Tarnocai et al., 2009; Zimov et al., 2006), whereas for the LGM, it is estimated up to 2300 Pg (Ciais et al., 2012). These soils therefore have huge carbon stocks. Increased climate warming between 17 and 12 ka BP went along with the oxidation of large amounts of SOC and the release of CO_2 contributing to a CO_2 increase of ca. 100 ppm in the atmosphere. Such changes are also proven for earlier transitions between glacials and interglacials. So far, many scientists attributed this rise of CO_2 to CO_2 degassing from the oceans. This has to be questioned, and the dynamics of permafrost carbon have to be better included in future climate models and in predictions of changing carbon cycles (Schuur et al., 2008).

Furthermore, carbon dynamics of permafrost soils are controlled by MAT and hence by integrated annual insolation. The glacial periods of the Early Pleistocene, lasting about 40 ka, correlate with earth's obliquity, which controls the integrated annual insolation of the high latitudes. Since the Middle Pleistocene, the permafrost expanded to the middle latitudes (45° N), where annual insolation is controlled by earth's eccentricity. This could explain, why, with the beginning of the Middle Pleistocene, the 40-ka cycles of the glacial periods have been replaced by 80–120 ka cycles, controlled by the coincidence of the obliquity and eccentricity cycles (Huybers, 2007).



■ **Fig. 2.2** Map showing the extension of the polar-subpolar zone, representative climographs and the main distribution of the RSGs in the Northern Hemisphere

2.3 Reference Soil Groups

2.3.1 Cryosols (CR)

Word Origin

Greek krýos = cold, ice.

Definition

Soils with a *cryic horizon* (symbol f), i.e. a year-round frozen soil layer (permafrost). During the short summer, the topsoil is thawing ('active layer'), which may cause water saturation and redoximorphic features above the *cryic horizon*. When the soil freezes again, churning (cryoturbation) may occur (symbol @) which may inhibit the formation of horizons that are really horizontal (Turbic*). Typical horizon sequences are therefore Ah-Bw@-Cf, O-Ah@-Bw@-Cf, Ah-Bwf-Cf or H-Ah-Cr@-Cf. The *cryic horizon* starts within 100 cm of the soil surface. If there are cryoturbation features within 100 cm it is sufficient that the *cryic horizon* starts within 200 cm. Due to slow OM decomposition, peat and bog layers are widespread (Histic*) although permafrost soils with thicker organic horizons are classified as Histosols (if directly above ice, 10 cm are sufficient for a Histosol). In semi-arid regions, ascending water may cause the formation of surface salt crusts (Salic*).

Physical Properties

- Under frozen conditions, ice contents vary between 30 and 75% by volume, in form of crystals, lenses or striae; massive ice with ≥ 75% by volume is indicated by the horizon symbol I;
- water saturation and redox processes are common due to the impermeable permafrost layer;
- organic horizons: during the thawing period loose with low density, high water content and air deficit;
- mineral horizons: at the soil surface, patterned ground is common; single-grain, platy or angular blocky structure in the topsoil, massive structure with high density in the subsoil; fine-textured layers have higher ice contents than the coarse-textured;
- multifarious forms of cryoturbation: polygon, drop, pocket, churned structures and mixed forms; hardening in case of desiccation; stress cutans possible because freezing is associated with an increase of volume and pressure. Large quantities of electrolyte-poor water can cause mobilisation and migration of clay and silt particles that may form coatings.

Chemical Properties

- Typically large stocks of organic matter (estimated global OC stocks in permafrost soils, including Cryic Histosols: 1700 Pg); little knowledge about C_{org} stabilization by freezing and association with clay minerals and oxides;
- CEC variable, in case of higher OM content, 40…60 $cmol_c\ kg^{-1}$ soil;
- BS variable, 20…100%;
- pH value (H_2O) from ≈ 4 (e.g. on quartzite) up to 8 (e.g. on limestone);
- N and P deficiency common, due to low mineralization rates, even if stocks are high.

Biological Properties

- Organic horizons: during the thawing period and if not water-saturated, remarkable microbial activity, especially in soils with high pH values;
- mineral horizons: during the thawing period, in the topsoil appreciable mineralization;
- if water saturation and *reducing conditions*: denitrification and methanogenesis.

Distribution

Many Cryosols develop in periglacial strata (e.g. solifluction layers), especially in fine-textured material.

Cryosols cover an area of approximately $1.8 * 10^9$ ha, worldwide. They occur in both the polar-subpolar zone and the more continental parts of the boreal zone. In North America, they dominate in the polar-subpolar zone (NE Canada) but are also widespread in the boreal zone (N and NW Alaska, NW Canada). In mountains, they are found in the alpine and nival belts. In Eurasia, they occur predominantly in Central and E Siberia, where they extend far south into the boreal zone (Central Siberian Highlands, Yakut Basin, E Siberian Mountains - 'light taiga'). This is the largest area of Cryosols (continental climate). They are rare in Scandinavia and in European Russia. Furthermore, they occur along the coastal areas of Greenland, Antarctica and on the islands of the Arctic and Antarctic Sea.

Land Use: Potential and Problems

Timber use in taiga and forest tundra; reindeer grazing in the moss and dwarf shrub tundra.

These ecosystems are very sensitive: risk of overgrazing and soil erosion (Scandinavia); damages to soils remain irreversible for decades or centuries; soil erosion and climate warming may cause thermokarst.

Global air circulation brings pollutants (e.g. Pb, Cd, PAHs, PCBs, biocides), emitted by industries or agriculture in the mid-latitudes or tropics, even into the polar-subpolar zone, where they accumulate by condensation at low temperatures. This effect, called 'global distillation', explains to some extent the high pollution levels in (sub)polar ecosystems.

As a consequence of climate warming, thin *cryic horizons* may melt completely and water, until now stagnated

2

above the *cryic horizon*, may percolate. This will allow an aerobic decomposition of the organic matter, which is much faster than the anaerobic one, and cause the emission of large amounts of CO_2.

Diagnostics

Cryosols have the following diagnostic horizon according to IUSS Working Group WRB (2015).

Cryic horizon

A cryic horizon has:

1. continuously for ≥2 consecutive years one of the following:
   (a) massive ice, cementation by ice or readily visible ice crystals; ***or***
   (b) a soil temperature of ≤0 °C and insufficient water to form readily visible ice crystals; ***and***
2. (a) thickness of ≥5 cm.

Qualifiers

Table 2.1 shows the qualifiers according to IUSS Working Group WRB (2015).

Table 2.1 The qualifiers of the Cryosol

Principal qualifiers	Supplementary qualifiers
Glacic	Abruptic
Turbic	Albic
Subaquatic/Tidalic/Reductaquic/Oxyaquic	Alcalic/Dystric/Eutric
Leptic	Andic
Protic	Arenic/Clayic/Loamic/Siltic
Folic/Histic	Dolomitic/Calcaric
Mollic/Umbric	Drainic
Natric	Fluvic
Salic	Gypsiric
Spodic	Humic/Ochric
Alic/Luvic	Limnic
Calcic	Magnesic
Cambic	Nechic
Hyperskeletic/Skeletic	Novic
Haplic	Ornithic
	Raptic
	Sodic
	Sulfidic
	Technic
	Tephric
	Thixotropic
	Toxic
	Transportic
	Vitric
	Yermic/Aridic

Related Groups in Other Classification Systems

- FAO Classification (FAO, 1988): Gelic…, Cryic… soil types.
- Soil Taxonomy (Soil Survey Staff, 2014): Gelisols (except Histels).

Profile Characteristics

Figure 2.3 shows the properties of a typical Cryosol and Fig. 2.4 the refreezing in autumn. Figure 2.5 presents two typical Cryosol profiles.

Soil-Forming Processes

Soil ice

At the beginning of the frost period, pore water freezes irregularly from the soil surface downwards. In fine-grained materials (silt, loam, clay), **ice lenses, ice layers and irregular ice bodies** (segregation ice) form at the freezing front, whereas in coarse-grained materials (sand, gravel), freezing of soil water in coarse pores will lead to the formation of compact **ice cement**.

If a soil abruptly cools down due to very low temperatures, vertical cracks with several mm of width can be formed due to thermal ice contraction. After warming, water seeps into the cracks and freezes to an initial **ice vein** (Fig. 2.6.a), which again and again centrally fractures during temperature drops and fills up with water afterwards. After long periods, (layered) **ice wedges,** up to several meters thick and > 10 m deep, can be formed (Fig. 2.6.b). Their isotopic composition ($\delta^{18}O$ and δD) can help to evaluate the regional paleoclimatic conditions. Ice wedges formed during very cold conditions mainly show more negative $\delta^{18}O$ and δD values than those of Holocene age. Global warming causes the thawing of ice wedges, and their hollow patterns fill with (mostly mineral) soil material. Such patterns document former stages with permafrost.

Cryoturbation

Seasonal cycles with freezing and thawing within the active layer (thawing zone) cause intensive material movement and mixing, especially in fine- to mixed-textured material (Fig. 2.6.c).

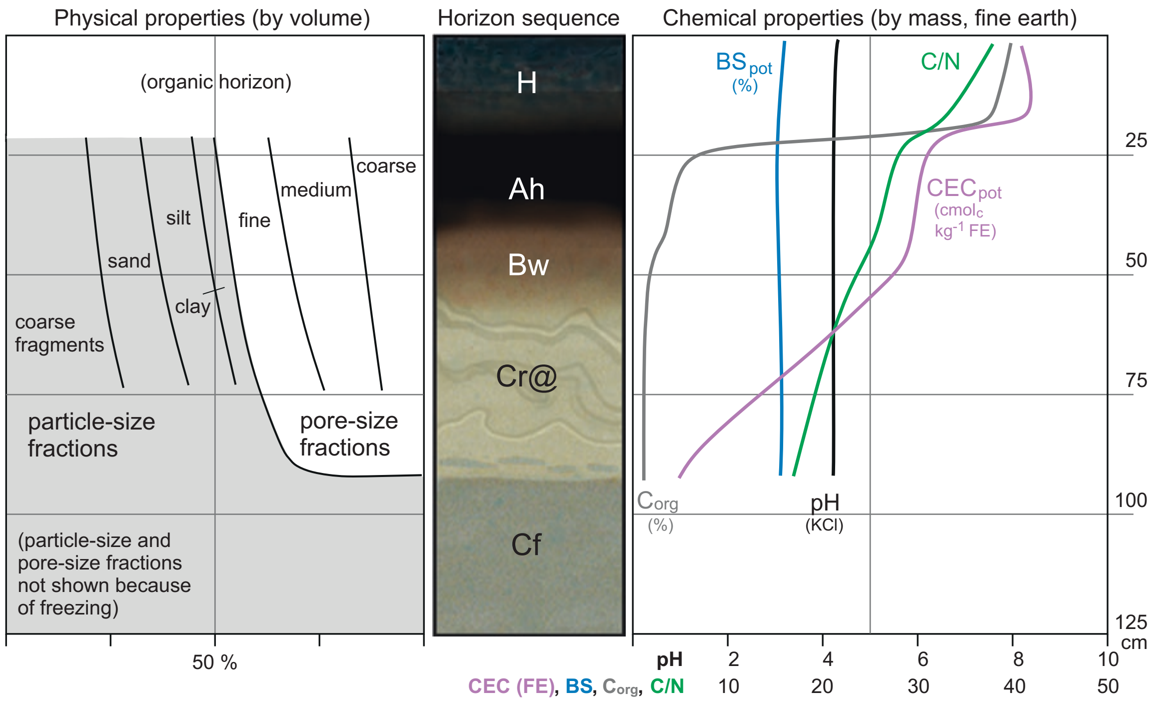


Fig. 2.3 Typical properties of a Histic Reductaquic Turbic Cryosol, developed from silicate-rich glacial till

Fig. 2.4 Refreezing of the active layer in autumn

Formation of polygons. When in autumn the active layer freezes again from the surface downwards, the volume of the material increases (9%) along a pressure gradient. Wetter silt- and clay-rich sections expand stronger during freezing and even form ice lenses; compared to sections with coarser particles, they develop an increased **frost heave** and bulge up to **thufurs**. On the surface of the bulge (1), frost debris drifts sidewards and forms a lateral debris edge (2) of oriented fragments ('patterned ground'). During melting in spring, the fine soil ice lens starts to shrink from the side, so that particles of the coarse debris fall down into the opening crack (3), and OM from the topsoil moves into the subsoil.

In stratified soils, ice pressure and gravity destroy the stratification forming interlocked structures. Thus, so-called pocket, snare, garland, churn, or drop soils are formed.

Solifluction (gelifluction)
Even on slopes with little inclination (≥ 2°), the topsoil layers which have melted during the warm season and have become increasingly water-saturated, start moving above the impermeable and still frozen subsoil, following gravity, and slowly flow downslope. Thus, mud layers with multifarious internal structures are formed, many of them interfingering with layers formed by cryoturbation. As a consequence, polygon nets drag out downslope forming stone stripes (Fig. 2.6.d).

Fig. 2.5 **(a) Cambic Glacic Cryosol (Siltic)** from N Siberia. Above a year-round frozen subsurface *cryic horizon* (Cf), siltic Ah and Bw horizons have been developed. The active layer is about 55 cm thick. (Photo: ©G. Guggenberger). **(b) Spodic Folic Turbic Cryosol** from Polar Ural Mountains. The *cryic horizon* starts at 150 cm below the surface. An earlier formed *spodic horizon* within the topsoil has been churned via cryoturbation. Horizon sequence O-Ah@-E@-Bhs@-Bw-Cf

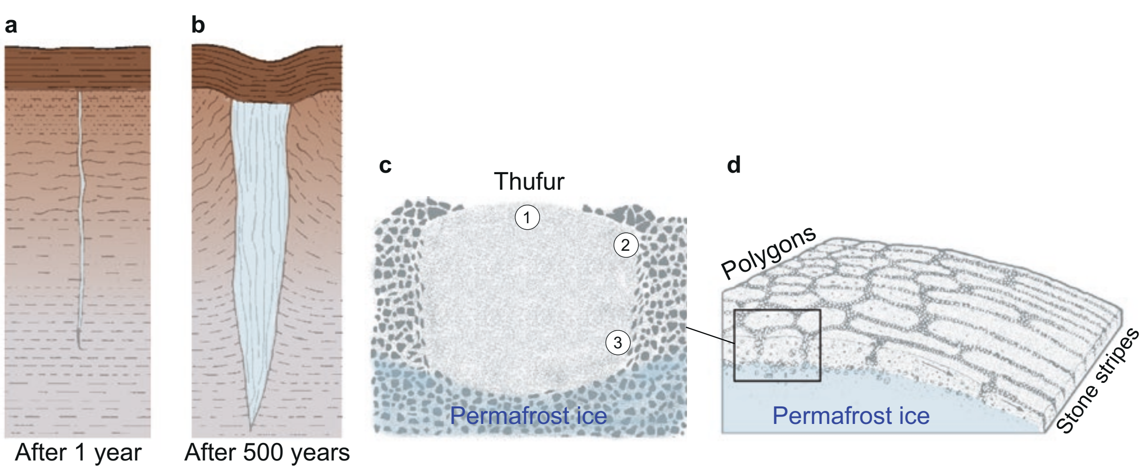


Fig. 2.6 Permafrost features: **(a)** ice vein; **(b)** ice wedge; **(c)** thufur; **(d)** polygon net and stone stripes. (**a**, **b** according to Embelton & King (1975), **c** according to Schreiner (1992) and **d** according to Wilhelmy (1974))

2.4 Landscapes and Soils

The following figures give examples of landscapes and soils of the polar-subpolar zone: Figs. 2.7, 2.8, 2.9, 2.10, 2.11, 2.12, 2.13, 2.14, 2.15, 2.16, 2.17, 2.18, 2.19, 2.20, 2.21 and 2.22.