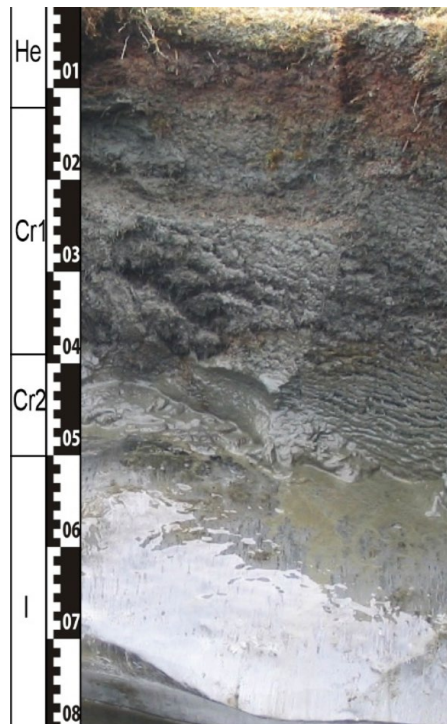


# WRB Documentation Centre

## Cryosols

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2024

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**Front page picture: Figure 1:** Histic Reductaquic Glacic Cryosol (Siltic, Endic, Eutric, Humic) Profile SV-2: Norway, Svalbard 78°11'39" N, 15°51'11" E, @C. Kabala

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## WRB Documentation Centre

### Abstract

*This text is a contribution to the WRB Documentation Centre that illustrates the Reference Soil Groups (RSG) and all their principal qualifiers (PQ) in the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022).*

*These lecture notes deal with the RSG of Cryosols. It provides the soil forming factors and the main characteristics of this RSG and reviews its classification at RSG and qualifier level. Examples of fully documented Cryosols with their principal qualifiers derived from expert sources are given in the “Typifying pedons” accompanying document. The “Historical review” accompanying document describes the changes in the evolving classification criteria for Cryosols since the FAO/Unesco Legend of the Soil Map of the World.*

*The WRB soil classification system will benefit from a core set of documented occurrences of Reference Soil Groups with their principal qualifiers as illustrated here. However, not all principal qualifiers could be documented and a call for contributions is made to fill the gaps in the present Cryosol collection.*

### Call for contributions:

Examples of fully documented (Photograph with tape, soil profile description and associated analytical data; with specification of the description protocol used, the methods for analyses applied and the units of the data) for Alic, Andic, Cambic, Coarsic, Haplic, Leptic, Luvic, Mollic, Natric, Oxyaquic, Protic, Retic, Salic, Skeletic, Spodic, Subaquatic, Tidalic, Umbric, Wapnic and Yermic Cryosols will be gratefully acknowledged (Name, title, Institution).

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## Introduction

The core concept of Cryosols comprises mineral and mineral-organic soils that typically have a cryic horizon (perennially frozen soil defined below) or cryoturbation features above a cryic horizon.

The characterization of Cryosols in this text was based on the ‘classical’ review written by Tarnocai (Driessen et al., 2001) and extended with information from various sources such as Kimble et al. (2004), Bockheim et al. (2006), and Bockheim (2015). The classification of Cryosols is given in the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022) with reference to the similarities and differences to Soil Taxonomy (Soil Survey Staff, 2022). Attention is paid to the evolution of classification of Cryosols in different editions of the World Reference Base for Soil Resources (Deckers et al., 1998; ISSS/ISRIC/FAO, 1998; IUSS Working Group WRB, 2006, 2007, 2010, 2015) in the accompanying report “Historical review”.

## Summary description of Cryosols

Connotation: frost-affected soils; from Gr. *kraios*, cold, ice.

Names: Cryosols are known as permafrost soils, frozen soils, cryomorphic soils or polar desert soils. Permafrost is a thermal condition where the temperature stays below 0 °C for more than two consecutive years. Cryosols are similar to Gelisols (defined below) in Soil Taxonomy (Soil Survey Staff, 2022) and Cryozems in Classification and Diagnostics of Soils of Russia (Shishov et al., 2004; Dokuchaev Soil Institute, 2008). Cryosols comprise the light-textured cryoturbated podzolic soils, and the medium- or heavy-textured cryoturbated gleyic mineral and mineral-organic soils that have frozen subsurface layers and show evidence of cryoturbation. Accumulations of ice such as ice crystals, ice lenses, ice layers (vein ice), ice wedges, or massive ground ice are often related to soil texture. For example, the fine-textured Cryosols have larger water capacity and thus contain more ice than coarse-textured Cryosols. Cryoturbated profiles have irregular or broken soil horizons, organic matter incorporated into the subsoil layers, sorted and nonsorted patterned features on the soil surface, and evidence of suprapermafrost gleization or organic matter accumulation. Freeze-thaw sequences and ice segregation are primarily responsible for the platy and lenticular structures of the mineral surface horizons. Vesicular pores may form in arid cryic regions. Cryosols occur in Antarctic, Arctic, Subarctic and Boreal regions affected by permafrost, notably on mountain slopes and in the depressions in lowlands. Cryosols are associated with sparsely to continuously vegetated tundra, subalpine, or lichen-covered areas, open-canopy coniferous and closed-canopy coniferous and deciduous taiga and boreal forests. Many Cryosols in Antarctica are in a cold desert environment and do not support any vegetation. Due to climate conditions, the short vegetation growing period, and the presence of frozen layers, Cryosols are considered unsuitable for agriculture, large-scale agriculture, but they can support small-scale farming plots (e.g. private greenhouses) and provide enough vegetation for extensive grazing of partly domesticated and wild animals such as caribou, reindeer, and musk ox.

## Classification of Cryosols

### **Cryosols definition as a Reference Soil Group**

Cryosols have been placed as the fourth RSG in the key to the WRB classification. Therefore, Cryosols are considered soils having the characteristics listed below, and not having diagnostic materials and horizons requirements in the three preceding RSGs (Histosols, Anthrosols and Technosols).

A cryic horizon is a perennially frozen soil horizon, at least 5 cm thick that has massive ice, cementation by ice or readily visible ice crystals or has insufficient water to form readily visible ice crystals. The temperature in the cryic horizon is continuously below 0 °C for 2 consecutive years or longer. The cryic horizon may develop in both mineral and organic material.

The definition of cryic horizon is not the same as the definition of permafrost. The permafrost thermal condition can occur in any material, including organic materials, unconsolidated mineral sediments, and bedrock (called continuous rock in WRB). The cryic horizon cannot be recognized in continuous rock, even if it has temperatures below 0 °C. Furthermore, unconsolidated sediments saturated with saline water do not freeze at 0 °C. Soils must be cold enough to freeze to develop a cryic horizon. As in dry unconsolidated sediments a cryic horizon will not form problems are arising to establish in the field Cryosols in dry permafrost zones in the present WRB definitions of Cryosols.

Cryosols (IUSS Working Group WRB, 2022) are defined as soils having a cryic horizon starting within 100 cm from the soil surface, or soils having cryic horizon starting within 200 cm from the soil surface if evidence of cryogenic alteration are recognizable within 100 cm of the soil surface (including the soil surface). Not all soils with a cryic horizon are Cryosols. Soils with a cryic horizon deeper than 200 cm, and some with a cryic horizon between 100 and 200 cm but without evidence of cryogenic alteration within 100 cm are not Cryosols. Evidence of cryogenic alteration include cryoturbation, frost heaving, cryogenic sorting, thermal cracking, ice segregation, decrease in mineral particle size, and patterned ground.

### **Comparison with similar soils in other classification systems**

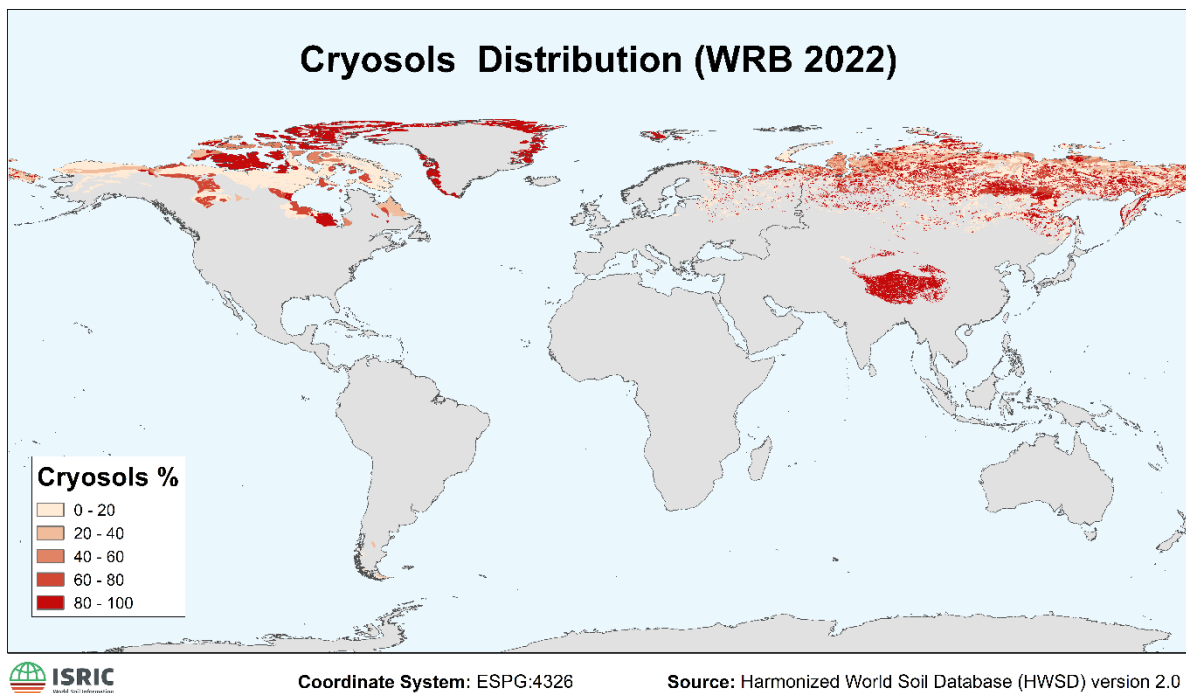
The Gelisols of Soil Taxonomy require permafrost within 100 cm of the soil surface or gelic materials within 100 cm of the soil surface and permafrost within 200 cm of the soil surface. Gelisols are first separated into Histels (organic soils), then Turbels (with cryoturbation), and then Orthels (without cryoturbation) (Soil Survey Staff, 2022). Cryosols in the Canadian System have similar great groups (Soil Classification Working Group, 1998). Gelisols key out before Histosols, whereas Histosols key out before Cryosols in WRB. Therefore, organic soils with permafrost are Gelisols in Soil Taxonomy but are Cryic Histosols in WRB. The difference is exacerbated by the different definitions of organic material in ST (>12% OC) and WRB (>20% OC). Within great groups of Turbels and Orthels, those with a histic epipedon key out first. In contrast, the Histic principal qualifier is the sixth choice in Cryosols. The differences between WRB and Soil Taxonomy in terms of classification of permafrost-affected soils can result in a larger extent of Gelisols than Cryosols on the soil maps (by partial inclusion of Histosols into Histels and Leptosols into Turbels).

Cryozems in Russian classification system (Dokuchaev Soil Institute, 2008) require having cryogenic horizon CR, which is dirty-brown or grayish-brown non-gleyed or weakly gleyed, unstructured or weakly structured mineral mass of more often of loamy granulometric

composition and non-differentiated by the chemical composition. The horizon lies beneath the organogenic horizon and directly above the frozen ground. As a rule, it has signs of permafrost disturbances in the form of a swirling pattern of the mineral mass and buried fragments of organogenic horizons, often confined to the permafrost part of the profile.

## Geographic distribution of Cryosols

Cryosols cover an estimated 18 million (mln) km<sup>2</sup>, or about 13% of the global exposed land surface area. Cryosols are pervasive in the ice-free areas of the high Arctic and the Antarctic and are widespread in the permafrost regions of the low Arctic and Subarctic region. They are discontinuous and sporadic in mountainous regions where permafrost occurs. Major areas of Cryosols are known from Russia (10 mln km<sup>2</sup>), Canada (2.5 mln km<sup>2</sup>), China (1.5 mln km<sup>2</sup>) and Alaska (1 mln km<sup>2</sup>). Smaller occurrences have been reported in permafrost regions in high elevation mountain regions such as the Alps, Andes, Himalayas, and Rocky Mountains, in Mongolia and northern Europe (Figure 1).



**Figure 2:** Distribution of Cryosols (FAO/IIASA, 2022). Additional areas occur in high-elevation or subpolar mountains, on the Antarctic coast south of New Zealand and on the Antarctic Peninsula South of South America.

The extent of Cryosols in the low Arctic and Subarctic may continuously decrease due to retreat of permafrost driven by climate change. However, new Cryosols may also appear as soils are exposed on the margins of retreating glaciers, particularly in the high mountains and the perimeter of Antarctica and Greenland.

## Soil forming factors and genesis of Cryosols

**Parent material:** a wide variety of unconsolidated materials, including glacial till and aeolian, alluvial, colluvial, and residual materials (regoliths) in which the soil forms. Wide-spread, Late Pleistocene syngenetic Ice Complex deposits reworked by paleopedogenesis are serving as parent material for modern Cryosols (Strauss et al., 2021).

**Climate:** Cryosols typically occur in cold and extremely cold climates where the mean annual air temperature is 0 °C or less, which sustains the presence of a cryic horizon in the soil profile.

**Age/Time:** Most Cryosols are considered young soils developed on Holocene landforms formed in glaciated or periglacial regions after Pleistocene glacier/ice sheet retreat or on recently created alluvial and colluvial landforms in those regions. Additionally, many Cryosols are 'rejuvenated' by cryomorphic processes such as gelifluction in sloping areas. Cryosols located on pre-Holocene landforms in Antarctica may represent relict or polygenetic soils of the Pleistocene age.

**Topography:** In the circumpolar zones, Cryosols occur on all landforms including river and lacustrine terraces, lowland plains, plateaus, hills, and mountains. In the lower latitudes, Cryosols occur typically in the higher elevation mountain areas with sufficiently cold climate or in peatlands in the areas of relict permafrost patches.

**Fauna and flora:** Cryosols are associated with sparsely to continuously vegetated alpine, subalpine, and tundra, open-canopy lichen coniferous forests and closed-canopy coniferous or mixed coniferous and deciduous forests. Soil biodiversity and the biological activity of Cryosols are limited by climate conditions. Additionally, the soil fauna is limited to species adapted to severely cold climates. In Antarctica there is sparse moss vegetation in locations where water accumulates on the land surface during snowmelt, with limited vegetation on Subantarctic Islands and the Antarctic Peninsula. In many regions there is minimal macroflora. Antarctic Cryosols have a microbial community including bacteria, fungi, nematodes and sparse occurrences of mites and springtails.

**Human influences:** Many Cryosols occur in less populated areas and remain in a natural or seminatural state. Extensive grazing of tundra on Cryosols with caribou, reindeer and musk oxen do not significantly change the soil properties. However, overgrazing can locally lead to the destruction of vegetation cover, soil erosion, and physical and chemical soil transformation. The more severe impact is related to agriculture, including soil drainage and the removal of the peat layer. This can change biological activity and thermal regime and may finally result in a subsequent destruction of permafrost (including the 'termokarsting' phenomena) and decrease in carbon stocks. Human activities related to oil and gas production, and coal and ore mining can degrade the soil surface and morphology of Cryosols, often in conjunction with pollution (e.g., from oil spills) and may cause changes in soil chemical and biological properties. Cryosols are also prone to indirect human impact, particularly due to global climate warming. Northern Hemisphere Cryosols act as carbon sinks in the present climate but warming of the circumpolar regions alters the thermal regime of the soils and increases the depth of the active layer. Warming enhances the decomposition of the soil organic matter. Previously 'fixed' carbon is released into the atmosphere as carbon dioxide (CO<sub>2</sub>) along with sometimes huge quantities of methane (CH<sub>4</sub>) which further contributes to global warming.

## Genesis of Cryosols

The essential feature of Cryosols is a 'perennially frozen' cryic horizon within 200 cm. Freezing can cover the entire soil volume during the colder seasons, but the upper part of the soil profile (the 'active layer' or 'transient layer' of permafrost) above the 'permanently frozen' layer thaws in the summer. Permanently frozen means the presence of massive ice, soil cementation by ice or readily visible ice crystals or soil temperatures below 0°C (if the water content is too low to form ice) for at least two consecutive years. The maximum depth of thaw can change during the year and differ between years in response to environmental and climatic conditions, fires, human-disturbance of the soil or vegetation, thickness, timing, and duration of snowpack, and climate changes. Thus, the near-surface active layer is highly dynamic and may contain pedological features developed in periods of deeper thawing. The active layer in Cryosols of the High Arctic (northernmost Arctic archipelago) normally extends down to 40 to 80 cm below the soil surface, whereas, in the more temperate part of the permafrost zone and in coarser soils in the permafrost zone, the active layer may extend below 100 cm. In the Ross Sea region of Antarctica, the maximum depth of thaw is usually between 20 and 40 cm, but ranges from near 0 cm at high altitudes to about 1 m in particularly sunny, sheltered, microclimates.

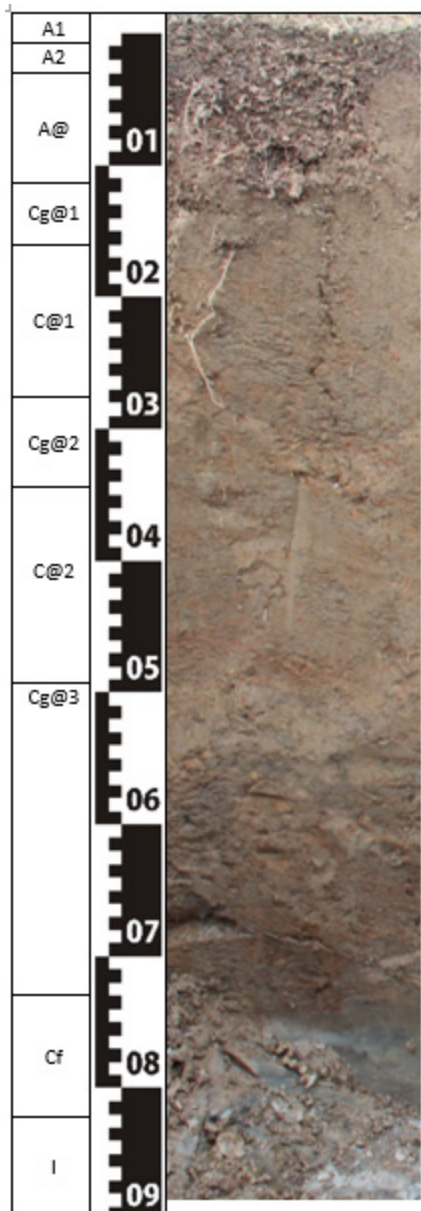
When the temperature drops, a freezeback occurs from the frost table upwards and from the soil surface downwards. The soil material between these freezing fronts comes under cryostatic pressure and, as a result, unfrozen materials are displaced and soil horizons are intermingled, contorted, and broken, forming characteristic cryogenic structures and cryoturbated soil horizons. Freezeback also causes rock fragments to be heaved and sorted, resulting in oriented features in the soil and a micro-topography of 'patterned grounds' at the surface often consisting of adjacent sorted polygons with more rocks and non-sorted areas with fewer rocks. Extremely low winter temperatures cause the frozen soil mass to shrink and crack through thermal contraction, usually in a polygonal pattern. Ice can build up in the cracks and form ice wedges.

Soil weathering and leaching are minimal in Cryosols of the High Arctic and Antarctica. However, along with deepening of the active layer toward the more southerly parts of the northern hemisphere permafrost zone, due to global climate warming, the accompanying pedogenic processes become more active, and E and B horizons occur more often. Gleyic or stagnic properties may develop following prolonged saturation of Cryosols with water, especially in the suprapermafrost horizons.

## Characteristics of Cryosols

### Morphology

Almost all Cryosols have a subsurface cryic horizon that contains accumulations of ice such as ice crystals, ice lenses, ice layers (vein ice), ice wedges or massive ground ice. The depth of the cryic horizon and, respectively, the thickness of the active layer influence other physical, hydrological and biological processes and soil productivity. Within the McMurdo Dry Valleys of Antarctica there are some areas where soil moisture contents are so low (<5%) that there is insufficient moisture to form visible ice.



Most Cryosols show evidence of cryoturbation in form of irregular or broken soil horizons, organic matter incorporated into the lower soil horizons or concentrated along the top of the permafrost table, oriented stones in the soil and sorted and non-sorted patterned ground features on the surface. The most common patterned grounds are earth hummocks, circles, nets, polygons, stripes, and steps.

Freeze-thaw sequences and ice segregation are primarily responsible for the characteristic granular, platy, blocky, and lenticular structure unit shape of the mineral surface horizons. Organo-mineral horizons that underlie the superficial organogenic ones often have oöid (“caviar-like”) post-cryogenic (inherited from ice segregation) soil structure. Vesicular pores may form in arid cryic regions that are largely free of plant roots. The subsurface horizons tend to become massive and densely packed because of the cryostatic pressure and desiccation that develops during freezeback, especially in fine-textured soils. The soils with high silt content are often thixotropic (liquify when shaken or stress is applied).

**Figure 3:** Turbic Glacial Cryosol (Siltic, Eutri 15°51'11" E. @ A. Bartos, M. Drewnik, M. Szymański

Salt crusts are reported on the surface of some Cryosols. Salt crusts develop in terms of increased evaporation from the soil surface, which may occur during dry summer periods. Massive salt layers, up to 50 cm thick, have been reported from Antarctica.

### **Mineralogical characteristics**

Cryosols are not distinguished by a specific mineralogy, which is largely dependent on the kind of parent material. Thus, Cryosols can range from extremely siliceous soils (similarly to Arenosols) to those that contain more weatherable minerals. In response to climate conditions, physical weathering typically prevails over chemical and biochemical weathering in the Antarctic, High Arctic, and high altitudes in the permafrost zone, and the opposite may be true in other parts of the permafrost zone.

### **Hydrological characteristics**

Low-elevation and southerly Arctic Cryosols typically experience an excess of soil moisture throughout the thawing (growing) season because the evapotranspiration remains minimal under low air and soil temperatures. Cryosols located in depressions or influenced by spring water are commonly covered with moss, which can lead to peat accumulation. Antarctic, High Arctic, and high-altitude Cryosols are typically dry, excluding a short thawing period. In soils characterised by high seasonal evapotranspiration, salts can accumulate in the topsoil horizons or on the soil surface as a salt crust.

### **Physical characteristics**

The physical properties of the active layer of Cryosols vary strongly in a short distance in texture and content of rock fragments, especially near the surface. Thixotropic soils are poorly trafficable during the thaw season, while other textures have greater strength. Non-thawed parts of the active layer are solidified with various amounts of ice in the form of segregated ice crystals, ice lenses, ice layers, and ice wedges.

The unique thermal characteristic that separates Cryosols from all other soils is the presence of a perennially frozen cryic horizon. Due to the cryic horizon, Cryosols have a steep vertical temperature gradient. In areas with 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, which are often peat-covered, can be 5° to 7°C lower.

### **Chemical characteristics**

The chemical properties of Cryosols, including pH, carbonates, cation exchange capacity, electric conductivity, and others, vary greatly and depend on the parent material and current input/output of substances in aeolian and fluvial deposition processes. Furthermore, cryoturbation can influence the vertical and horizontal diversification of chemical soil properties. The nitrogen, potassium and phosphorous contents of dry mineral Cryosols are generally low and adsorbed to the surface organic matter. However, Cryosols that are developed on loess-like Late Pleistocene Ice Complex deposits often contain significant amounts of nutrients and organic carbon which are inherited from the earlier stages of pedogenesis. The carbon pools increase noticeably in moist Cryosols with organic (peat)

layers. Furthermore, cryoturbated Cryosols may contain even 27-73 kg/m<sup>3</sup> of organic carbon, whereas the carbon pools of non-cryoturbated Cryosols are estimated at 4 to 5 kg/m<sup>3</sup> (Kimble et al., 2004). Nitrogen and phosphorus contents can be very high within or near the animal (birds, mammals) breeding colonies (e.g., penguin colonies with accumulations of guano have N and P contents as high as 10% in some samples) and where seabirds nest on rock outcrops of coastal cliffs and islands.

### Biological characteristics

Unfavourable thermal and hydrological conditions of Cryosols result in very low or low macroinvertebrate biological activity, particularly in Antarctica, the High Arctic and arid high-altitude permafrost areas. In waterlogged sites, this is evidenced by accumulation of undecomposed plant tissues (peat). Soil macroinvertebrate biological activity increases noticeably in the southern parts of the northern hemisphere permafrost zone and is clearly evidenced by the relatively advanced development of B horizons. Soil microbial activity in all Cryosols is comparable with that of other biomes.

### Soilscape relationships of Cryosols with other Reference Soil Groups

Cryosols in the High Arctic are often found adjacent to Histosols, Gleysols, and Fluvisols in lowlands, or to Leptosols and Regosols in the high-altitude mountains. Under more favourable climate conditions, Cryosols coexist in mosaics with Cambisols, Brunic Arenosols, Podzols, and Planosols. In the Antarctic, Cryosols are found in proximity to Regosols, Leptosols, Cambisols, and Histosols (Bockheim et al., 2015). In more southerly and lower-altitude hilly and mountainous topography, Cryosols are found on north-facing slopes, while the south-facing slopes normally are covered with non-permafrost soils. In the urban, industrial and mining areas, Cryosols occur in mosaics or are replaced with Technosols.



**Figure 4:** Cryosols soilscape of the Yukon Valley, Alaska: forefront: ice-filled polygonal thermal cracks; left-back: pingo. @C. Tarnokai

In areas recently burned by hot wildfires, and areas cleared of native vegetation, the surface layers lose most of their organic matter, the cryic horizon thaws and the active layer thickens or disappears for decades or more, and the soils behave and classify as Cambisols, Leptosols, and Regosols. Jelinski et al. (2024) reported that under a warming climate, up to 69% of Alaskan Gelisols are susceptible to taxonomic change by the end of the century. Gelisols in Northern Alaska would be the most resilient to taxonomic change and those in Western and Interior Alaska would be most susceptible to taxonomic change. Some Histels would become Histosols, some Turbels and most Orthels would become Cambisols, Andosols, Podzols, Phaeozems, Umbrisols, and Regosols.

## Land use and management of Cryosols

Due to harsh climate conditions, short vegetation growing period and the presence of frozen layers, Cryosols are considered unsuitable for large-scale agriculture; however, they can support enough vegetation for extensive grazing of animals, including caribou, reindeer and musk oxen. They can also support small-scale farming plots within settlements (especially rural ones). Cryosols support extensive forestry in the areas where climate conditions allow the closed-canopy coniferous or mixed coniferous and deciduous forests.

Many Cryosols occur in less populated areas and remain in a natural or seminatural state. The ecosystem services of these soils, especially related to global biodiversity and carbon sequestration, should be maintained and protected against transformation. Best management practices such as maintaining or replacing surface cover of mosses and higher vegetation whenever the native cover is removed or destroyed through forestry, mining, or infrastructure installation. Agricultural clearing of Cryosols must be avoided. Road building, building construction, and pipeline projects may require radiators to prevent permafrost thawing and anthropogenic thermokarst or thaw lake development. Due to climate change, cities built on permafrost require artificial deep-seated deep-freezing of building foundations so as to prevent building collapse during above-average hot summers.

## Principal qualifiers

The principal qualifiers are the main subdivisions of the RSG used for detailed naming and mapping. The following principal qualifiers have been recognized for Cryosols in IUSS Working Group WRB (2022):

**Glacic:** indicative of soils having a layer containing  $\geq 75\%$  ice, starting within 100 cm from the soil surface.

**Turbic:** indicative of soils having features of cryogenic alteration (cryoturbation) within 100 cm from the soil surface.

**Subaquatic:** being permanently submerged by water not deeper than 200 cm.

**Tidalic:** being affected by tidal water, i.e. located between the line of mean high water springs and the line of mean low water springs.

**Reductaquic:** identifies soils having a layer above a cryic horizon and starting within 75 cm of the soil surface, saturated with water during the thawing period.

**Oxyaquic:** identifies soils having a layer starting within 75 cm of the soil surface, saturated with water during the thawing period, but not having gleyic or stagnic properties in any layer within 100 cm of the mineral soil surface.

**Leptic:** indicative of soils having continuous rock starting  $\leq 100$  cm from the soil surface.

**Histic:** indicative for soils having a histic horizon, which consists of poorly aerated organic material.

**Andic:** identifies soils having a layer or layers consisting of weathered pyroclastic materials. Defined as having within 100 cm of the soil surface one or more layers with andic or vitric properties with a combined thickness of  $\geq 30$  cm, of which  $\geq 15$  cm has andic properties.

**Mollic:** identifies a dark-coloured surface horizon with high base saturation, moderate to high content of organic carbon and a well-developed soil structure (mollic horizon).

**Umbric:** identifies a thick, dark-coloured surface horizon with low base saturation, moderate to high content of organic carbon and a well-developed soil structure (umbric horizon).

**Natric:** identifies soils having an illuvial horizon enriched with clay and exchangeable sodium (natric horizon).

**Salic:** indicator of accumulation of high concentrations of soluble salts (i.e. salts more soluble than gypsum) at shallow depth at  $\leq 100$  cm (salic horizon).

**Spodic:** identifies soils having a subsurface acid horizon enriched with organic matter and oxalate-extractable aluminium and iron (spodic horizon).

**Retic:** identifies soils having and interfingering of the light-coloured coarser-textured material into the finer-textured argic or natric horizon.

**Alic:** identifies soils having an illuvial horizon enriched with clay (argic horizon) with a high effective CEC and a high level of exchangeable aluminium.

**Luvic:** identifies soils having an illuvial horizon enriched with clay (argic horizon) with a high effective CEC and a low level of exchangeable aluminium.

**Calcic:** indicative for large accumulations of secondary calcium carbonate ( $\geq 15\%$ ) at shallow depth ( $\leq 100$  cm); a calcic horizon.

**Wapnic:** indicative for large accumulations of secondary calcium carbonate (calcic horizon) within organic material, starting within 100 cm from the soil surface.

**Yermic:** identifies soils having the characteristics such as desert pavement, desert varnish, ventifacts, a platy structure and vesicular pores. Yermic properties occur on mineral soil surface in warm and cold deserts.

**Protic:** identifies soils showing no soil horizon development other than a cryic horizon.

**Cambic:** having a subsurface horizon showing evidence of soil formation that ranges from weak to relatively strong and with soil aggregate structure at least in half of the volume of the

fine earth (cambic horizon), not consisting of light-colored fine earth (claric material) and starting  $\leq 50$  cm from the mineral soil surface.

**Coarsic:** having  $< 20\%$  (by volume, related to the whole soil) fine earth, averaged over a depth of 75 cm from the soil surface or to limiting layer starting  $> 25$  cm from the soil surface, whichever is shallower.

**Skeletal:** indicative for soils having a high, but not extremely high percentage of coarse fragments. It is defined as having  $\geq 40\%$  (by volume) coarse fragments ( $> 2$  mm) averaged over a depth of 100 cm from the mineral soil surface or to limiting layer, whichever is shallower.

**Haplic:** means having none of the principal qualifiers mentioned above.

## Supplementary qualifiers

It is not the intention at this stage to document all supplementary qualifiers in the WRB Documentation Centre, therefore, these qualifiers are not discussed in detail. Supplementary qualifiers allow for further characterisation of the soil unit at an individual/local level. There are 39 different supplementary qualifiers foreseen in Cryosols in IUSS Working Group WRB (2022).

- Qualifiers that specify soil texture and its distribution with depth (**Arenic**, **Clayic**, **Loamic**, and **Siltic**).
- Qualifiers that indicate characteristics related to parent rock, vertical discontinuity and geomorphic processes: **Calcaric** (dispersed calcium carbonate of primary/lithogenic origin), **Dolomitic** (dispersed dolomite of primary/lithogenic origin), **Gypsic** (dispersed gypsum of primary/lithogenic origin), **Fluvic** (fluvial/alluvial material present in soil profile), **Limnic** (lacustrine material present in soil profile), **Litholinic** (subsurface stone layer), **Novic** (recently accumulated materials overlying the buried horizon), **Ornithic** (remnants of birds or bird activity, such as bones, feathers, and sorted coarse fragments of similar size, and very high content of phosphorus), **Raptic** (lithic discontinuity within 100 cm depth), **Tephric** (layer with unweathered volcanic glass, glassy aggregates, other glass-coated primary minerals), **Vitric** (layer containing partly weathered glassy pyroclastic materials).
- Qualifiers that indicate special chemical characteristics of the soil related to pedogenesis: **Alcalic** (especially high pH related to the presence of sodium bicarbonate in the topsoil), **Dystric** (low base saturation), **Eutric** (high base saturation), **Humic** ( $> 1\%$  soil organic carbon weighted over 50 cm), **Magnesian** (having an exchangeable Ca to Mg ratio of  $< 1$ ), **Ochric** ( $\geq 0.2\%$  soil organic carbon in the upper 10 cm and no mollic or umbric horizon are present), **Sodic** (accumulation of exchangeable Na and Mg not accompanied by natric horizon), **Sulfidic** (having an inorganic sulfidic sulphur).
- Qualifiers that indicate specific morphological, physical, and hydrological characteristics of the soil: **Abruptic** (abrupt increase of clay content within 100 cm depth), **Albic** (eluvial layer comprising a light-coloured material), **Biocrustic** (biological surface crust), **Evapocrustic** (thick saline surface crust), **Puffic** (surface crust comprising of readily soluble salts), **Drainic** (presence of a surface drainage system), **Epic** (here: cryic horizon starts with 50 cm from the soil surface) presence of a surface drainage system), **Endic** (here: cryic horizon starts between 50 and 100 cm from the soil surface) presence of a surface drainage system), **Dorsic** (here: cryic horizon starts 100 and 200 cm from the soil surface), **Folic** (thick litter layer in topsoil),

**Nechic** (uncoated sand grains in dark-coloured acid topsoil), **Thixotropic** (temporary water saturation caused by a frozen layer).

- Qualifiers that indicate human interventions: **Pyric** (presence of charcoal), **Technic/Kalaic** (presence of dispersed/packed artefacts), **Toxic** (concentration of toxic substances), **Transportic** (a layer of material added by intentional human activity, originating from outside the near vicinity).

## References and further reading

Bockheim, J. G. (2015). *Cryopedology* (p. 173). London: Springer.

Bockheim, J. G., & Tarnocai, C. (1998). Recognition of cryoturbation for classifying permafrost-affected soils. *Geoderma*, 81(3-4), 281-293.

Bockheim, J. G., Mazhitova, G., Kimble, J. M., & Tarnocai, C. (2006). Controversies on the genesis and classification of permafrost-affected soils. *Geoderma*, 137(1-2), 33-39.

Bockheim J. G. (2014) Global Distribution of Cryosols with Mountain Permafrost: An Overview, *Permafrost and Periglacial Processes* 26, 1–12, doi: 10.1002/ppp.1830.

Bockheim, J.G., Lupachev, A. V., Blume, H. P., Bölter, M., Simas, F. N. B., & McLeod, M. (2015). Distribution of soil taxa in Antarctica: A preliminary analysis. *Geoderma* 245–246, 104-111. ISSN 0016-7061. <https://doi.org/10.1016/j.geoderma.2015.01.017>.

Campbell, I. B., Claridge, G. G., Campbell, D. I., & Balks, M. R. (1998). The soil environment of the McMurdo dry valleys, Antarctica. *Ecosystem dynamics in a polar desert: the McMurdo Dry Valleys, Antarctica*, 72, 297-322.

Deckers, J.A., Nachtergaele, F.O., Spaargaren O.C. (eds), 1998. *World Reference Base for Soil Resources, an Introduction*. 165p. Acco Leuven / Amersfoort, ISBN 90-334-4124-1 Driessen, P., Deckers, J., Spaargaren, O. and Nachtergaele, F. (eds), 2001 *Lecture notes on the major soils of the world*. *World Soil Resources Report Nr 94*, 334 p. FAO, Rome.

ISSS/ISRIC/FAO. 1998. *World Reference Base for Soil Resources*. *World Soil Resources Report No. 84*. FAO Rome.

IUSS Working Group WRB. 2006. *World Reference Base for Soil Resources 2006*. *World Soil Resources Report No. 103*, FAO, Rome.

IUSS Working Group WRB. 2007. *World Reference Base for Soil Resources 2006, First Update 2007*. FAO, Rome.

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 Report No. 106*, FAO, Rome.

IUSS Working Group WRB, 2022. *World Reference Base for Soil Resources*. *International soil classification system for naming soils and creating legends for soil mapping*. 4<sup>th</sup> edition. International Union of Soil Science, Vienna, Austria.

Jelinski, N. A., Pastick, N. J., Kholodov, A. L., Sousa, M. J. & Galbraith, J. M. (2024). Estimates of soil taxonomic change due to near-surface permafrost loss in Alaska. *Soil Science Society of America Journal*, 88:1626-1646. <https://doi.org/10.1002/saj2.20729>.

Jones, A., Stolbovay, V., Tarnocai, C., Broll, G., Spaargaren, O., & Montanarella, L. (2010). Soil atlas of the northern Circumpolar Region (pp. 144-pp).

Kabala, C., & Zapart, J. (2009). Recent, relic and buried soils in the forefield of Werenskiold Glacier, SW Spitsbergen. *Polish Polar Research*, 161-178.

Karelin, D., Goryachkin, S., Zazovskaya, E., Shishkov, V., Pochikalov, A., Dolgikh, A., ... & Kraev, G. (2020). Greenhouse gas emission from the cold soils of Eurasia in natural settings and under human impact: Controls on spatial variability. *Geoderma regional*, 22, e00290.

Kimble, J. (Ed.). (2004). *Cryosols: permafrost-affected soils*. Springer Science & Business Media.

McLeod, M., Bockheim, J. G., & Balks, M. R. (2008). Glacial geomorphology, soil development and permafrost features in central-upper Wright Valley, Antarctica. *Geoderma*, 144(1-2), 93-103.

Mueller, G., Broll, G., & Tarnocai, C. (1999). Biological activity as influenced by microtopography in a cryosolic soil, Baffin Island, Canada. *Permafrost and Periglacial Processes*, 10(3), 279-288.

Shishov, L. L., Tonkonogov, V. D., Lebedeva, I. I., & Gerasimova, M. I. (2004) Classification and Diagnostics of Soils of Russia. *Oikumena, Smolensk [in Russian]*. 342p

Soil Survey Staff, 2022. *Keys to Soil Taxonomy*, 13th edition. USDA Natural Resources Conservation Service.

Tarnocai, C., & Bockheim, J. (2011). Cryosolic soils of Canada: genesis, distribution, and classification. *Canadian Journal of Soil Science*, 91(5), 749-762.

Tarnocai, C., & Zoltai, S. C. (1978). Earth Hummocks of the Canadian Arctic and Subarctic. *Arctic and Alpine Research*, 10(3), 581-594.

Zech, W, Schad, P., Gerd Hintermaier, E., 2021. *Soils of the World*. Springer, ISBN: 978-3-540-30460-9, 256p.

### **Additional readings:**

Acree, A., Weindorf, D.C., Galbraith, J.M., Jelinski, N.A., & Paulette, L. (2020). Characterization of Gelolls in northern Alaska, USA. *Soil Science Society of America Journal*, 84(3), 818-832. <https://doi.org/10.1002/saj2.20064>.

Broll, G., & Tarnocai, C. (2020). The Nature of Arctic Soils. In: Goldstein, M.I., DellaSala, D.A. (Eds.), *Encyclopedia of the World's Biomes*, vol. 2. Elsevier, pp. 295–302. ISBN: 9780128160961.

Dietze, M., Bartel, S., Lindner, M., & Kleber, A. (2012). Formation mechanisms and control factors of vesicular soil structure. *CATENA*, 99:83-96. ISSN 0341-8162. <https://doi.org/10.1016/j.catena.2012.06.011>.

Hoberg, E., Kutz, S., Galbreath, K., & Cook, J. (2003). Arctic biodiversity: From discovery to faunal baselines - Revealing the history of a dynamic ecosystem. *Journal of Parasitology*. 89:S84-S95.

Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., Delaloye, R., et al. (2019). Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km<sup>2</sup> scale, *Earth-Science Reviews*, 193, 299-316. <https://doi.org/10.1016/j.earscirev.2019.04.023>