Earth-Science Reviews 101 (2010) 190–206

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

The principles of cryostratigraphy

Hugh French [a,*], Yuri Shur [b]

[a] Departments of Geography and Earth Sciences, University of Ottawa, Canada
[b] Department of Civil and Environmental Engineering, University of Alaska Fairbanks, Fairbanks, Alaska, USA

ARTICLE INFO

Article history:
Received 11 September 2009
Accepted 13 April 2010
Available online 5 May 2010

Keywords:
frozen ground
permafrost
geocryology
Quaternary geology
ground ice
cryostructure

ABSTRACT

Cryostratigraphy adopts concepts from both Russian geocryology and modern sedimentology. Structures formed by the amount and distribution of ice within sediment and rock are termed *cryostructures.* Typically, layered cryostructures are indicative of syngenetic permafrost while reticulate and irregular cryostructures are indicative of epigenetic permafrost. 'Cryofacies' can be defined according to patterns of sediment characterized by distinct ice lenses and layers, volumetric ice content and ice-crystal size. Cryofacies can be subdivided according to cryostructure. Where a number of cryofacies form a distinctive cryostratigraphic unit, these are termed a 'cryofacies assemblage'. The recognition, if present, of (i) thaw unconformities, (ii) other ice bodies such as vein ice (ice wedges), aggradational ice and thermokarst-cave ('pool') ice, and (iii) ice, sand and gravelly pseudomorphs is also important in determining the nature of the freezing process, the conditions under which frozen sediment accumulates, and the history of permafrost.

Contents

1. Introduction . . . 190
2. Frozen ground . . . 191
3. Epigenetic, syngenetic and polygenetic permafrost . . . 191
4. Ground ice . . . 192
5. Cryostructures in bedrock . . . 193
6. Cryostructures in poorly-lithified sediments . . . 193
7. Cryostructures of epigenetic and syngenetic permafrost . . . 194
8. Thaw unconformities . . . 195
9. Aggradational ice . . . 198
10. Cryostratigraphic mapping . . . 200
11. Icy bodies . . . 201
12. Ice, sand, and soil pseudomorphs . . . 204
13. Conclusions . . . 204
Acknowledgments . . . 204
References . . . 204

1. Introduction

Cryostratigraphy is the study of frozen layers in the Earth's crust. It is a branch of geocryology. It first developed in Russia where the study of ground ice gained early attention (Shumskii, 1959; Katasonov, 1962, 1969) and subsequently led to highly-detailed studies (e.g., Vtyurin, 1975; Popov, 1973; Gasanov, 1963; Gravis, 1969; Rozenbaum, 1981; Zhestkova, 1982; Shur, 1988; Romanovskii, 1993; Dubikov, 2002; Seigert et al., 2002; Schirrmeister et al., 2008) that are unparalleled in North America. Cryostratigraphy differs from traditional stratigraphy by explicitly recognizing that perennially-frozen sediment and rock (permafrost) contain structures that are different from those found in unfrozen sediment and rock.

* Corresponding author. 10945 Marti Lane, North Saanich, BC, Canada V8L 6B3.
E-mail address: hmfrench@shaw.ca (H. French).

0012-8252/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.earscirev.2010.04.002

Cryolithology is a related branch of geocryology and refers to the relationship between the lithological characteristics of rocks and their ground-ice amounts and distribution.

The principal aim of cryostratigraphy is to identify the genesis of perennially frozen sediments and to infer the frozen history of earth material. Today, the permafrost region currently occupies approximately 23% of the earth's land surface. During the cold periods of the Pleistocene it is generally accepted that an additional 20% or more experienced permafrost conditions. Accordingly, knowledge of cryostratigraphy is essential for Quaternary scientists working in the northern latitudes. A second aim of cryostratigraphy is to document the ground-ice conditions in different types of perennially-frozen rock and soil. The latter has significant geotechnical importance in Russia, Canada, Alaska, Svalbard, Greenland and Tibet. A third objective is to correlate sequences of ground ice in contemporary permafrost regions with horizons of former ground ice in past permafrost regions.

2. Frozen ground

Frozen ground may be *diurnal*, *seasonal* or *perennial* in nature. The latter is termed *permafrost*, namely, earth material that remains below 0 °C for at least two years (Sumgin, 1927; Muller, 1943). In general, the mean annual temperature of permafrost in its stable thermal state is lowest at the permafrost table and increases with depth in accordance with the geothermal gradient. In all types of frost, the physics underlying the freezing process are the same. The major difference between seasonal and perennial frost is that seasonal frost disappears in summer. Seasonal freezing in areas without permafrost involves one-sided freezing (i.e., from the surface downward) whereas seasonal freezing in the permafrost region is often two-sided (i.e., both downwards from the surface and upwards from the underlying perennially-frozen material). Diurnal frost, a relatively well known phenomenon, is not considered in this paper.

In the case of permafrost, the near-surface layer that thaws and freezes annually is termed the *active layer*. Burn (1998) has discussed the terminology and definition of the active layer. In general, active-layer thickness may vary from less than 15–30 cm in peaty terrain and Quaternary-age sediments to over 5.0 m in many igneous and metamorphic rocks exposed to the surface. Thickness also varies from year to year and from locality to locality, depending on controls such as ambient air temperature, slope orientation and angle, vegetation, drainage, snow cover, soil and/or rock type, and water content. In field probing, the active-layer thickness includes the uppermost part of the permafrost wherever either the salinity or clay content of the permafrost allows it to remain unfrozen even though the material remains 'cryotic' (i.e., below 0 °C). The base of the active layer (i.e., the depth of annual thaw) may also vary on annual, decadal and millennia time scales. Accordingly, the *transient layer* includes the typically ice-rich layer marking the long-term position of the contact between the active layer, as defined above, and the upper part of permafrost (Shur et al., 2005). As a result, it is necessarily to recognize a four-layer system of the active layer that incorporates a transient layer at the interface between the active layer and underlying permafrost. These concepts are illustrated in Fig. 1.

Most of the permafrost that occurs in the high northern latitudes today is termed *present permafrost*. It is either in equilibrium with current climate or either aggrading or degrading under prevailing cold-climate conditions. Permafrost may also be *relict*, or ancient, having formed under conditions that no longer exist and which is now preserved under present environmental conditions. Most is usually Late-Pleistocene in age. It can be argued that nearly all present permafrost is relict because climate has warmed in the last 150 years following the Little Ice Age. Permafrost that does not exist today is referred to as *past permafrost* (French, 2008). Its previous existence in now-unfrozen rock and sediment is commonly inferred from disrupted bedrock and the presence of frost- or thaw-related structures. Most past permafrost is of Late-Pleistocene age although permafrost is known to have occurred in earlier geological times.

3. Epigenetic, syngenetic and polygenetic permafrost

Permafrost that forms after deposition of the host sediment or rock is termed *epigenetic.* The time lag between accumulation and perennially freezing of epigenetic permafrost reaches thousands and millions of years. By contrast, permafrost that forms at the same time as continued cold-climate sedimentation and causes the base of the active layer to aggrade upwards is termed *syngenetic*. This sedimentation may be alluvial, colluvial (i.e. slump or gravity-induced), aeolian, or lacustrine in nature. By definition, syngenetic permafrost is of the same age (approximately) as the sediment in which it is formed. It means that transformation of sediments at the bottom of the active layer into a perennially-frozen state occurs simultaneously with sedimentation on the soil surface. The concepts of epigenetic and syngenetic permafrost growth are illustrated in Fig. 2. However, many thick permafrost bodies are best regarded as *polygenetic,* in which one part is syngenetic and

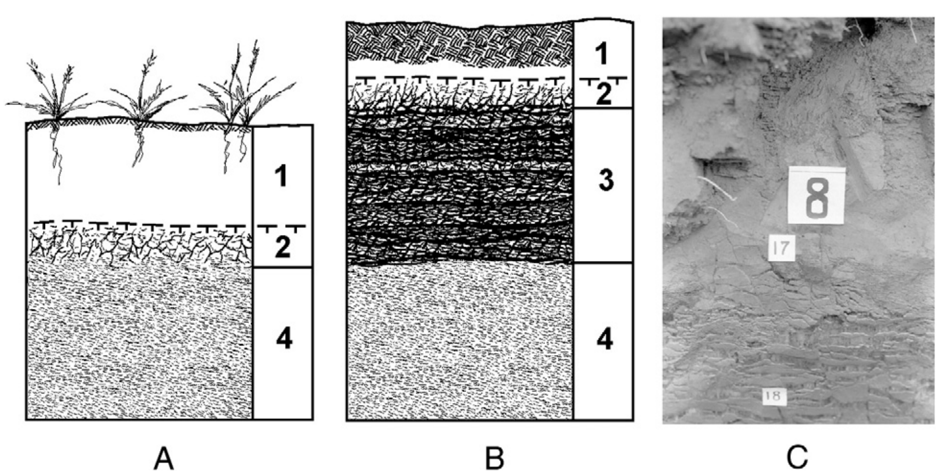

Fig. 1. The nature of the active layer and the upper permafrost. (A). The three-layer model (Shur et al., 2005). Legend: 1 — active layer, 2 — transient layer, 3 — permafrost. (B). The four-layer model of the active layer-permafrost interface with two layers in the transition zone originally proposed by Shur (1988). Legend: (1) — *Active layer* (seasonal freezing and thawing); 2 — *Transient layer* (due to variations during about 30 years (the period defining the contemporary climate); 3 — *Intermediate layer* formed from part of the original active layer due to environmental changes, primarily organic accumulation, containing aggradational ice. Together, the transient layer and intermediate layer comprise the Transition Layer (4) *Permafrost* (freezing and thawing at century to millennial scales). (C). A photo showing the active layer (friable, at top, above large marker), the transient layer (compact, ice poor, below large marker) and the intermediate layer (ice-rich with crustal (ataxitic) cryostructure, near bottom, small markers). The sediments are Yedoma series, Kular, Northern Yakutia, Russia. Large marker is 5 × 5 cm, smaller markers are 2 × 2 cm. Photo: Y. Shur.