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CHARLES TARNOCAI (*) & FERENC SCHWEITZER (**)

CRYOGENIC FEATURES IN CANADA AND HUNGARY AND THEIR SIGNIFICANCE FOR PAST CLIMATE

ABSTRACT: TARNOCAI C. & SCHWEITZER F., *Cryogenic features in Canada and Hungary and their significance for past climate.* (IT ISSN 0391-9838, 1998).

Pleistocene deposits were examined in the Paks, Bábolna and Mogyoród areas of Hungary. Contorted soil horizons resulting from cryogenic processes in paleosols were found in the sand deposits near Paks. Various wedge-shaped features and sand involutions were found in gravel deposits in the Bábolna and Mogyoród areas. Sand wedges, ice wedge casts (former ice wedges), and frost cracks filled with sand are commonly found in these gravel deposits. The average height of the sand wedges is 1-2 m, but some are as high as 3 m. The sand in these wedges is vertically layered, suggesting that frost cracking occurred a number of times, with subsequent filling of the crack with sand material.

Sand wedges, frost cracks and ice wedges all develop in permafrost environments, and are currently actively forming in the Continuous Permafrost Zone in Canada. Cryoturbated soils, on the other hand, occur in all permafrost areas, but are most common in the Widespread Permafrost Zone and Continuous Permafrost Zone. Cryoturbated sandy soils, however, usually occur only in the Continuous Permafrost Zone in Canada. The well-developed sand wedges, frost cracks, ice wedge casts and cryoturbated soils found in Hungary suggest that the Carpathian Basin was a permafrost area during a cold, glacial part of the Pleistocene. At that time this area was most likely underlain by continuous permafrost.

KEY WORDS: Patterned ground, Paleoclimate, Permafrost, Canada, Hungary.

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Depositi del Pleistocene sono stati studiati nelle zone di Paks, Bábolna e Mogyoród in Ungheria. Presso Paks sono stati rinvenuti orizzonti di suoli contorti in depositi sabbiosi quale risultato di processi criogenici, mentre nelle zone di Bábolna e Mogyoród entro depositi ciottolosi sono state rinvenute strutture conformate a cuneo e involuzioni. Cunei sabbiosi, impronte di cunei di ghiaccio (antichi cunei di ghiaccio) e fratture riempite di sabbia sono d'altra parte comuni nei depositi grossolani. L'altezza media dei cunei sabbiosi è di 1-2 m, ma alcuni possono raggiungere 3 m. Esiste una stratificazione verticale dei letti di sabbia, ciò che suggerisce la ripetizione nel tempo di queste rotture del suolo da gelo, con il conseguente riepimento delle fratture con discesa delle sabbie.

Cunei di sabbia, poligoni da gelo e cunei di ghiaccio si sviluppano negli ambienti dove è presente il permafrost e sono normalmente attivi nella Zona del Permafrost Continuo in Canada. Suoli crioturbati, d'altra parte, si trovano in tutte le aree a permafrost, ma sono molto diffusi nella Zona del Permafrost Diffuso e in quella del Permafrost Continuo. I suoli crioturbati sabbiosi si rinvengono invece solo in quest'ultima zona. I ben sviluppati cunei sabbiosi, i poligoni da gelo, i cunei di ghiaccio e i suoli crioturbati dell'Ungheria suggeriscono che nel bacino Carpatico esistesse un'area con sviluppo di Permafrost verosimilmente continuo durante un periodo freddo (glaciale) del Pleistocene.

TERMINI CHIAVE: Suoli strutturati, Paleoclima, Permafrost, Canada, Ungheria.

INTRODUCTION

During the glacial periods of the Pleistocene, Hungary was subject to a cryogenic environment that produced various periglacial features. The cold climate during these glacial periods resulted partly from Hungary's unique geomorphological setting in the Carpathian Basin. The Carpathian mountain chain, which surrounds this large basin, creates an almost closed climatic situation, thus producing climatic conditions not found elsewhere in Europe. This unique climatic situation is still characteristic of Hungary, as it was during the Pleistocene epoch (Rónai, 1961). As a result, the climate of Hungary during the glacial periods was different from the cool and humid Mediterranean climate to the south and the glaciated oceanic climate of northwestern Europe (Dylik, 1963). In effect, Dylik seems to imply that the climate in Hungary during the glacial periods of the Pleistocene epoch was somewhat similar to the climate of the continental steppe regions to the east.

As a result of these cold climatic conditions in the Pleistocene epoch, various types of cryogenic soils and periglacial features developed and are found in well-preserved fossil forms in various deposits. Dylik (1963) summarizes the periglacial features of Hungary and discusses their ori-

(*) *Agriculture and Agri-Food Canada, Research Branch, 960 Carling Avenue, Ottawa, Canada, KIA 0C6.*
(**) *Geographical Research Institute, P.O. Box 64. H-1388 Budapest, Hungary.*

gin and development while Pécsi (1961, 1964 a, b, and c) provides detailed descriptions, including diagrams and photographs, of these features with the locations in which they occur. Dylik & Maarleveld (1967) reviewed European and North American literature relating to periglacial features such as frost cracks, frost fissures, and polygons and outlined on a map the southern limit of these features in Europe. The Pleistocene permafrost limits in western and central Europe are described by Maarleveld (1976), Kaiser (1960) and Poser (1948).

Present climatic and, thus, environmental conditions are very different in Canada from those in Hungary. While Hungary's climate is temperate, a large part of the area of Canada (40%) is currently underlain by either discontinuous or continuous permafrost. Thus, the periglacial features that today exist only in fossil form in Hungary are found in various forms and stages of development in this huge permafrost landscape. The distribution of the various permafrost zones in Canada is given by Harris (1986), Heginbottom (1984) and Johnston (1981), while the characteristics of these zones in relation to aerial climate are provided by Zoltai (1995), Nelson (1989) and Brown (1978).

Considerable data on the characteristics and classification of patterned ground types in Canada (Washburn, 1956, 1980) has been generated during the past several decades. Their development, especially that of ice wedges, is discussed by Zoltai & Tarnocai (1974), Mackay & McKay (1976) and Mackay (1986, 1984, 1974, 1972), while winter cracking of the frozen ground is discussed by Mackay (1993, 1975, 1973). Much work has been done on the characteristics and development of various types of ground ice (Mackay, 1976 and 1974; Mackay & Dallimore, 1992), and on cryoturbation and cryogenic soil features (Tarnocai & Zoltai, 1978; Mackay & McKay, 1976; Zoltai & Tarnocai, 1974).

In this paper the relict cryogenic features found in Hungary are compared to similar features active in the permafrost regions of Canada. The conditions under which these cryogenic features develop and occur will be used to interpret and predict climatic and permafrost conditions in Hungary during the cold glacial periods of the Pleistocene epoch.

DESCRIPTION OF SITES IN HUNGARY

Pleistocene deposits were examined in the Mogyoród, Bábolna, and Paks areas of Hungary (fig. 1). The site in the Mogyoród area is located in a gravel pit 15 km northeast of Budapest, in the northern part of the Gödöllö Hills. The geological section at this site is composed of two very different deposits. The older, lower deposit in which the sand wedges and other cryogenic features were found is an Upper Pliocene Paleo-Danube alluvial fan. The more recent, upper deposit in this section is an eolian sand. It and the contemporary soil developed on it show no evidence of cryogenic features.

The site in the Bábolna area is located in northwestern Hungary. Sand wedges, ice wedge casts and polygonal patterns were found in a gravelly alluvial deposit. The site in the Paks area is located in south-central Hungary, near the western shore of the Danube (Duna) River. At this site cryogenic soil features were found in a buried, cryoturbated paleosol developed on eolian sand deposits.

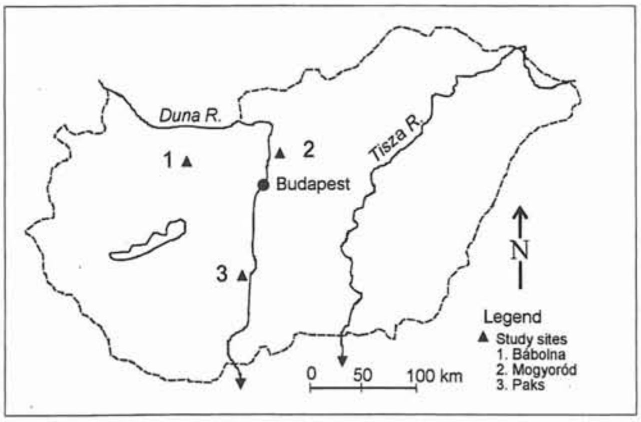

FIG. 1 - Location of sites examined in Hungary.

DISTRIBUTION OF PERMAFROST IN CANADA

Permafrost is defined as ground (soil or rock) that remains at or below 0°C for at least two consecutive years (Harris & *alii*, 1988). Permafrost is most commonly associated with various types of ice (ice-bonded permafrost), but if there is insufficient interstitial water the permafrost is dry (dry permafrost).

Permafrost distribution in Canada shows a latitudinal zonation. In the south it is discontinuous, while in the north it is continuous (fig. 2) Two zones are identified in the discontinuous portion, the Sporadic and the Widespread Discontinuous Permafrost Zones (Harris, 1986; Heginbottom, 1984; Johnston, 1981). In its most southerly occurrence the permafrost is sporadic, occurring under less than 30% of the area (Heginbottom, 1984), and is found mainly in peatlands as islands in a generally unfrozen terrain (Sporadic Discontinuous Permafrost Zone, SPZ). Farther north the permafrost becomes widespread, occurring under 30-80% of the landscape (Heginbottom, 1984), and is found in both organic (peatlands) and mineral terrain (Widespread Discontinuous Permafrost Zone, WPZ). In the most northerly regions all land surfaces, even under shallow water bodies, are underlain by permafrost (Continuous Permafrost Zone, CPZ). South of the southern limit of the Discontinuous Permafrost Zone permafrost can occur at high elevations in mountainous areas. These areas belong to tne Alpine Permafrost Zone. The thickness of the permafrost varies greatly, depending on location. It is no more than a few metres thick in the southern part of the SPZ, increasing to 30-50 m in the WPZ, and can be as deep as 500 m in the CPZ (Brown, 1967).

The mean annual air temperatures associated with these permafrost zones in Canada range from 0° to –5.5°C

FIG. 2 - Permafrost zones in Canada (Harris, 1986; Heginbottom, 1984; Johnston, 1981).

in the SPZ (Brown, 1978), –5.5° to –8.3°C in the WPZ (Nelson, 1989), and –8.3° to –17.0°C in the CPZ (Zoltai, 1995).

CRYOGENIC FEATURES IN CANADA

Patterned ground and cryogenic soils occur commonly in all of these permafrost regions, but their frequency and types differ somewhat from zone to zone (tab. 1). Patterned ground *(e.g.,* circles, nets and hummocks) occurs only rarely in the SPZ, but is common in the WPZ and very common in the CPZ. Ice-wedge polygons (fig. 3A, B and C), a form of patterned ground, do not occur in the SPZ, but have a similar distribution to other patterned ground forms in the WPZ and CPZ. Sand wedges that have formed during the Holocene (active sand wedges) occur mainly in the northern part of the CPZ. Similarly, cryoturbated soils are found only on wet, fine-textured ma-

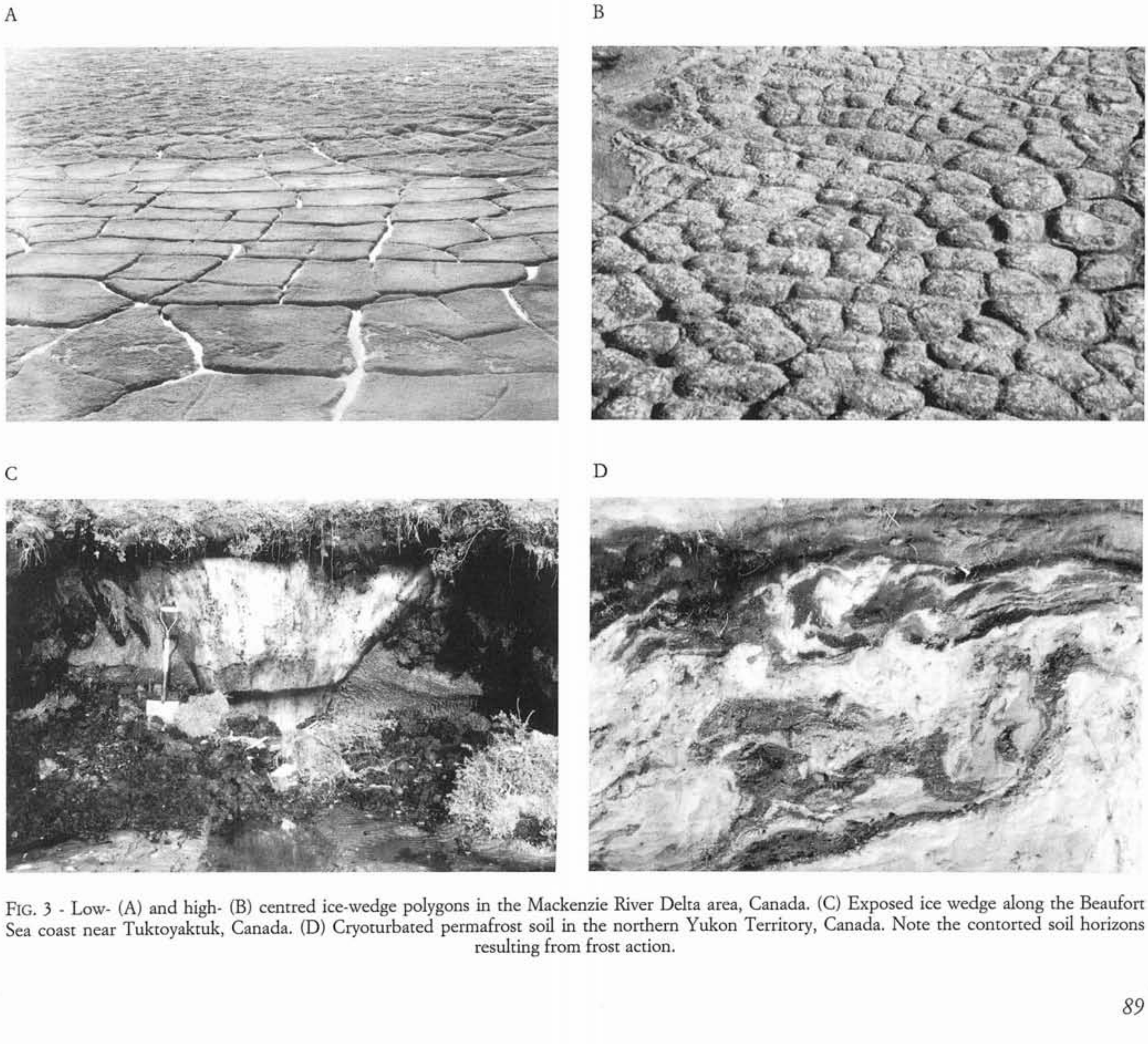

FIG. 3 - Low- (A) and high- (B) centred ice-wedge polygons in the Mackenzie River Delta area, Canada. (C) Exposed ice wedge along the Beaufort Sea coast near Tuktoyaktuk, Canada. (D) Cryoturbated permafrost soil in the northern Yukon Territory, Canada. Note the contorted soil horizons resulting from frost action.

terials in the SPZ, but they are the dominant soils in the WPZ, and the only soils in the CPZ. In the CPZ cryoturbation is even found in soils that occur on sandy materials (fig. 3D).

TABLE 1 - Cryogenic soil features in various permafrost zones

Cryogenic features	*SPZ*	*WPZ*	*CPZ*
Circles, nets, and hummocks	few	common	very common
Ice-wedge polygons	none	some	very common
Sand wedges	none	none	some
Cryoturbation	localized	very common	very common

CRYOGENIC FEATURES IN HUNGARY

Mogyoród site

Sand wedges, ice wedge casts (former ice wedges), and frost cracks filled with sand are commonly found in a gravel pit near Mogyoród. The site examined in detail is shown in fig. 4. The geological section at this site is composed of two very different deposits. The lower deposit is an Upper Pliocene alluvial fan of Paleo-Danube origin overlain by a much younger sandy deposit, probably of eolian origin. A thick, red paleosol has developed on the lower deposit while a contemporary soil has developed on the surface of the younger deposit. The colour (5YR 5/8) and thickness of the red paleosol indicate that it most likely developed in a much warmer climate than currently exists, and that such a climate operated for a long period of time. The redness of this paleosol (rubification) is attributed to the presence of hematite. Hematite formation usually takes place in a warm climate with mean annual air temperatures of 7°C or greater and total annual precipitation of as little as 500 mm (Schwertmann & *alii*, 1982; Torrent & *alii*, 1980). Sand wedges found in the red paleosol have an average vertical dimension of 1-2 m, but some are as much as 3 m (fig. 5A). On the basis of other western and central European information these sand wedges probably developed in the Late Weichselian (Würm) glacial period, possibly betwecn 17 and 20 Ka BP. Numerous, mainly horizontal but some vertical, cracks 2-5 mm wide filled with calcium carbonate are present in the red paleosol. The origin of these cracks is most likely associated with vein ice development in a permafrost environment. Later, in a non-permafrost environment, these cracks filled with calcium carbonate illuviated from the contemporary soil. It also should be pointed out that the sand in these wedges is vertically layered, suggesting that frost cracking occurred a number of times, with subsequent filling of the crack with sand material. In addition, vertically oriented cracks, 50 cm or slightly more in width, were found, and were interpreted as being former frost cracks filled with sand (fig. 5B).

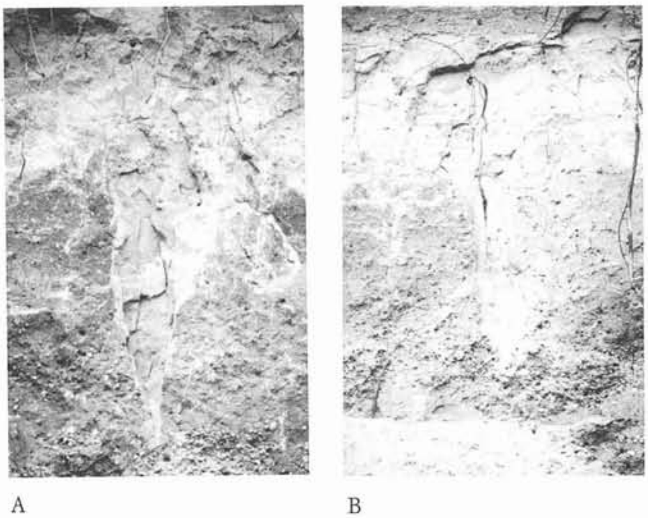

FIG. 5 - Sand wedge in the red paleosol (A), and a former frost crack filled with sand (B). Mogyoród site, Hungary.

Bábolna site

Various wedge-shaped features and sand involutions were found in a Bábolna gravel pit. The ice wedge casts in this gravel pit developed when former ice wedges melted and the wedge space filled with the surrounding gravelly materials (fig. 6A). It should be pointed out that ice wedge casts are a very good indicator of a former permafrost environment since ice wedges develop only in permafrost. The vertical dimension of the wedges is 0.5-1 m and, in areas where the surface has been bladed by a bulldozer, the polygonal pattern is clearly visible. No red paleosol is present at this site, but sand wedges have developed in the gravel deposit.

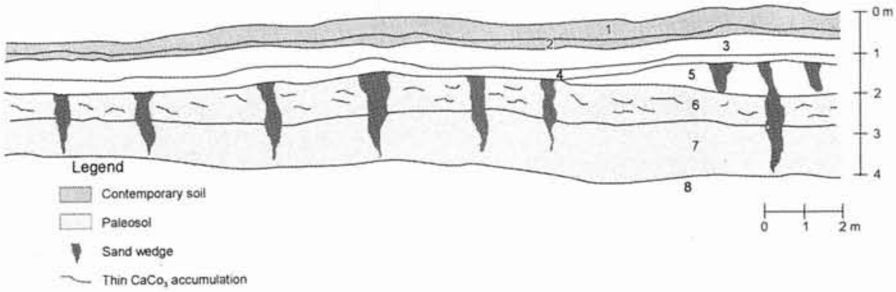

FIG. 4 - Cross section showing the various deposits, soils, and sand wedges in the Mogyoród site. The properties of the deposits are as follow: 1) Recent, sandy-textured soil (7.5YR 4/4); 2) Soil horizon with pedogenic $CaCO_3$ accumulation; 3) Windblown sand (10YR 6/6); 4) Gravel; 5) Gravelly sand; 6) Sandy gravel (5YR 5/8); 7) Gravelly sand (5YR 5/8); 8) Upper Pliocene gravelly alluvium of Paleo-Danube origin.

A

B

FIG. 6 - (A) Ice wedge cast in a gravel deposit, Bábolna site, Hungary. (B) A buried paleosol with contorted soil horizons resulting from cryoturbation, and a former frost crack filled with sand (centre of photo), Paks site, Hungary.

Paks site

Contorted soil horizons in paleosols were examined in the sand deposits near Paks (fig. 6B). Two brownish layers, representing the B horizons of two distinct paleosols, were identified in the exposed profile in these sand deposits. These paleosols are overlain by a thick sand layer on which the contemporary soil has developed. The B horizons of both paleosols are contorted and disrupted as a result of cryoturbation. In addition, the B horizon of the lower paleosol is dissected by a wedge-shaped sand body that was identified as a sand wedge. Closer examination of these paleosols revealed strong mottles, suggesting that a fluctuating water table affected this horizon. Thin organic layers associated with what seem to be a former vertical crack were also observed. All of the soil features in this paleosol were interpreted as being the result of cryogenic processes.

CRYOGENIC FEATURES AND THEIR CLIMATIC SIGNIFICANCE

Frost cracks, ice wedges and sand wedges all develop in permafrost environments and are still actively forming in the CPZ in Canada. Thermal cracking, the mechanism for their formation, takes place when frozen earth material is subjected to rapid cooling with resulting shrinking and cracking. The resulting frost cracks can be filled either with snow or water or with sand. In the case of ice wedges, these cracks are filled with snow or water during snow melt. Since these cracks always extend into the permafrost, the moisture quickly freezes to form the ice wedge. Ice wedge casts develop when these ice wedges melt. When there is insufficient moisture from snow or water to form ice wedges, the frost cracks fill with sand, leading to the development of sand wedges. The presence of sand wedges thus indicates the presence of a very cold, but dry, climate. The soil surface is usually devoid of vegetation and covered with a desert pavement.

Cryoturbated soils occur in all permafrost areas, but are most common in the WPZ and CPZ. Cryoturbated sandy soils, however, usually occur only in the CPZ in Canada. Cryogenic processes, the mechanism for the formation of cryoturbated soils, are driven by the presence and mobility of unfrozen soil water. The resulting cryoturbated soils are characterized by irregular and broken soil horizons, involutions, organic intrusions and oriented rock fragments.

The well-developed sand wedges, frost cracks, ice wedge casts and cryoturbated soils found in Hungary suggest that the Carpathian Basin was a permafrost area during a cold, glacial part of the Pleistocene epoch. At that time this area was most likely underlain by continuous permafrost, with mean air temperatures as low as those now occurring in the CPZ in Canada.

CONCLUSIONS

The mean annual air temperatures in Canada range from 0° to –5.5°C in the SPZ, –5.5° to –8.3°C in the WPZ and –8.3° to –17.0°C in the CPZ. Patterned ground (circles, nets and earth hummocks) occurs only rarely in the SPZ, but is common in the WPZ and very common in the CPZ. Ice-wedge polygons are common in the WPZ and very common in the CPZ; active sand wedges are found only in the CPZ. Cryoturbated soil features occur in all permafrost zones in Canada, but they are most common in the WPZ and CPZ.

Fossil sand wedges and ice wedge casts were found in gravelly alluvial deposits in Hungary. The sand wedges are about 1-2 m in vertical dimension, but some of them are as much as 3 m. Fossil sand wedges, ice wedge casts and frost cracks filled with sand were found in a gravel pit near Mogyoród. Wedge-shaped features, sand involutions and polygonal patterns were found in the Bábolna gravel pit, while cryoturbated soil features were found in a buried paleosol in the Paks area.

The presence of fossil sand wedges, frost cracks, ice wedge casts and cryoturbated soils in Hungary suggests that the Carpathian Basin was an area of continuous permafrost with mean air temperatures of –8.3° to –17.0°C during a cold, glacial part of the Pleistocene epoch.

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