NATURE, OCCURRENCE AND ORIGIN OF DRY PERMAFROST

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Abstract

Dry permafrost may be defined as a material that remains below 0°C for two or more years in succession but that has insufficient interstitial ice to become cemented. Dry permafrost has a very low moisture (ice) content (≤5% volumetric basis) and occurs in areas receiving <100 mm annual precipitation and where sublimation and evaporation exceed the water-equivalent precipitation. Likely restricted to ice-free area of Antarctica (e.g., the "dry valleys"), dry permafrost may be confused with a deep active layer in coarse-textured sediments, especially in the High Arctic, central Yakutia, and in cold-arid alpine environments. The thickness of dry permafrost ranges from a few decimeters to at least 5 m. Although the origin of dry permafrost is unknown, it likely originates from sublimation of moisture from ice-cemented permafrost in cold-dry environments over periods of excess of 18,000 yr.

Introduction

There is a lack of information and some confusion on the meaning of the term "dry permafrost." Dry permafrost was defined by Ferrians et al. (1969) as a material that remains below 0°C for two or more years in succession but that has insufficient interstitial moisture to be cemented. Brown and Kupsch (1974) defined dry permafrost as perennially frozen soil or rock with an ice content lower than the pore volume so that it does not yield excess water on thawing. According to a standard definition by Van Everdingen (1976), dry permafrost "contains neither free water nor [free] ice." No limits have been set on the moisture content or degree of cementation for a material to qualify as dry permafrost.

The aims of this paper are to determine the characteristics, geographic distribution, and factors responsible for the formation of dry permafrost.

Methods

We summarized data from the published literature for sub-polar and polar deserts (high arctic), cold desert (Antarctica), and dry alpine areas throughout the world, including mean annual precipitation (water-equivalent), mean annual air temperature, active layer thickness, and gravimetric moisture content of the active layer and the upper permafrost. These data were used to identify regions with dry permafrost, as opposed to deep, dry active layers.

Because several studies suggest that the depth to ice-cemented permafrost increases over time (Ugolini, 1964; Ugolini and Bull, 1965), we plotted thickness of the active layer + dry permafrost as a function of time for subxerous, xerous, and ultraxerous soils in Antarctica using the data set described in Bockheim and Wilson (1992).

Results and discussion

Site Characteristics

The analysis was limited to the areas depicted by Tedrow (1991) as the polar and sub-polar deserts in the Northern Hemisphere and the cold desert and polar desert in the Antarctic region. Therefore, all of the sites included in the analysis had a mean annual air temperature of -4.4°C or colder (Tables 1 and 2). The mean annual precipitation varied from ~15 mm yr^{-1} for Vanda Station, Antarctica to ~700 mm yr^{-1} in maritime East Antarctica. Permafrost temperatures in the "dry valleys" of Antarctica at a depth of 10 m range from -16°C to -26°C (Decker and Bucher, 1977). In the zone of continuous permafrost in North America and northern

Table 1. Properties of the active layer and the upper permafrost in the High Arctic of North America and Greenland

Location	Latitude	Longitude	Mean ann. precip. (mm)	Mean ann. temp. (C)	Active layer Thickness (cm)	Active layer Moisture content (%)	Permafrost moist. (%)*	Reference
Ellesmere Island	81°49'N	71°W	67	-19.7				1
Hazen					16-78	6.3-50 (15 cm)	med.-high ice	
Tanquary Fiord	81°24'N	76-77°W			15-64	5-51 (15 cm)	100	
Kongsfjord, Svalbard	79°N	12-16°E	385	-5.8	55-130		ice cement	12
Inglefield Land, Greenland	78°31'N	70°55'W	132	-17.3	15-91		(some dry frost)	5
Isachsen, Ellef Ringnes Is.	78°17'N	103°22'W	98	-18.7	28-42		(some dry frost)	3
Mould Bay, Prince Patrick Is.	76°14'N	119°20'W	85	-17.4	25-74		(some dry frost)	2,3
Bathhurst Island	76°N	97-102°W			30-46	12-32	42-91 (ice cement)	8, 13
Resolute, Cornwallis Island	74°44'N	94°55'W	130	-16.2	13-64	10-18	ice cement	6
Zackenberg, Greenland	74-75°N	21°W	214	-10.3	35->65		ice cement	7
Sachs Harbor, Banks Island	73°23'N	121°54'W	100	-14.4	>60		(some dry frost)	4
Mesters Vig, Greenland	72°14'N	23°55'W	373	-9.7	50-200		ice cement	11
Boothia Peninsula	70°10'N	94°37'W			~110	12-20	33-45**	13
Boothia & N. Keewatin	68-70°	92-96°W			50-107	11-74	19-99**	9
Ivik	69°37'N	134°20'W			>55	63-66	60	9, 14
Tuktoyaktuk	69°35'N	131°48'W			30-36	26-33	106-169	13, 14
Northwest Terr., Y67	68°47'N	134°00'W				31-36	79-196	14
Yukon Terr. , Y66	68°45'N	138°05'W			10-12	26-28	4.7-137	14
Northwest Terr.	68°44'N	134°03'W			~50	30-46	78**	13
Keewatin	68°30'N	92°52'W			~50	22-39	39-91**	13
Yukon Terr., Y54	68°25'N	137°30'W			34	22-242	184-1818	14
Northwest Terr., Y52	68°15'N	135°45'W			82	36-41	40-76	14
Northwest Terr.	68°07'N	133°28'W			>20	1-21	34-40	9
Baffin Island	66-67°N	65-66°W	336	-8.0	13-110	7.8-55 (15 cm)	ice cement	9, 10

* Reported on a gravimetric basis except where specified.
** Reported on a volumetric basis.
References: 1 = Tarnocai et al., 1991; Tarnocai and Gould, 1996; 2 = Tedrow, 1966; Tedrow et al., 1968; 3 = Everett, 1968; 4 = Tedrow and Douglas, 1 5 = Tedrow, 1970; 6 = Cruikshank, 1971; 7 = Jakobsen, 1992; 8 = Tarnocai, 1976; 9 = Tarnocai, unpublished; 10 = Birkeland, 1978; Bockheim, 1979a; Evans and Cameron, 1979; 11 = Washburn, 1965; Ugolini, 1966a, b; 12 = Mann et al., 1986; Sletten, 1988; 13 = Tarnocai, 1978; 14 = Zoltai and Tarno

Russia, permafrost temperatures at depths of 15 to 25 m range between -5°C and -12°C (Brown, 1967; Bigl, 1985).

Active layer thicknesses ranged from 15 to 20 cm in interior valleys of Antarctica to depths in excess of about 200 cm in central Greenland and maritime East Antarctica (Tables 1 and 2). However in most Antarctic soils, the depth to ice-cemented permafrost is greater than the depth of penetration of the 0°C isotherm at the warmest time of the year. Therefore, the concept of an active layer may not be appropriate for these soils (Campbell and Claridge, 1987).

The lowest gravimetric moisture contents of the active layer were recorded for the dry valley region of Antarctica, with values ranging from <1 to 3%, followed by coastal localities of Antarctica (1-10%) (Table 1). The moisture content of the active layer at the High Arctic sites ranged from 10 to 50%.

Ice-cemented permafrost is ubiquitous in the High Arctic; however, "dry frost" was reported in the Queen Elizabeth Islands and northeast Greenland, but no temperature or moisture data were provided to validate these interpretations. The gravimetric moisture content of ice-cemented permafrost in the High Arctic ranged from 42 to over 100% for organic materials (Table 1). Volumetric moisture contents ranged from 33 to 99%. For a coarse-textured soil with a bulk density of 1.74 g cm^{-3}, the volumetric moisture content of a fully saturated soil is 38% (Campbell et al., 1994). Therefore, any material with a volumetric moisture content in excess of 38% contains "excess ice," i.e., is supersaturated.

Ice-cemented permafrost occurs widely in Antarctica, particularly in coastal regions and along the edge of the polar plateau. The gravimetric moisture content of ice-cemented permafrost is comparable to that in the High Arctic, commonly ranging from 10 to 100% (Table 2). The amount of moisture required for cementation of sandy materials in Antarctica may be as low as 5 to 10% (Berg and Black, 1966; Campbell et al., 1994). According to Jones and Lomas (1983), frost heave occurs only in sediments when the moisture content at 31 kPa is 10% or greater. Patterned ground is either absent or poorly expressed in areas with dry permafrost (Black and Berg, 1963; Ugolini et al., 1973). Dry permafrost in the dry valleys of Antarctica (denoted by an asterisk in Table 2) contains ≤3% moisture by weight, similar to values in the active layer. Cameron (1971) observed that the driest Antarctic soils had moisture contents approaching or similar to the driest desert soils from temperate or hot desert regions.

In arid regions of interior Antarctica, dry permafrost is underlain by ice-cemented permafrost. Based on data

Table 2. Properties of the active layer and the upper permafrost in continental Antarctica

Location	Latitude	Longitude	Elev. (m)	Mean ann. precip. (mm)	Mean ann. temp. (C)	Active layer Thickness (cm)	Active layer Moisture content (%)	Permafrost moist. (%)**	Reference
Interior Antarctica									
Sør Rondane	71°51'S	24°15'E	1200	~180	-18.5	8-30	1.2-10	--	1
Beacon Valley	77°48'S	160°44'E	1250	~160	-20	24-44	0.3-4	1.7-8.9	2,3,4
Beacon Valley	77°48'S	160°44'E	1300	~160	-20	30-40	0.3-2.6	1.7-1.8*	4
Beacon Heights	77°50'S	160°45'E	2200	~160	-20	15-20	1.0-1.5	3-30	5
Wright Valley	77°32'S	161°40'E	275	45	-20	30-40	0.3-2.9	1.6-2.6*	5,6,7
Wheeler Valley	77°12'S	162°42'E	1300	~160	-20	15-18	0.8-1.7	9.5-144	8,9
Coombs Hill	76°48'S	159°50'E	2200	~160	-20	15-20	3	3*	5
McMurdo Sound									
E. Wright Valley	77°28'S	162°32'E	400	~188	-18	15-35	1.5-4.0	10	3
E. Taylor Valley	77°39'S	162°55'E	375	~188	-18	25-30	2.0-3.5	10-50	3
E. Taylor Valley	77°36'S	163°40'E	1-8	~188	-18	25-30	1.0-9.0	10-15	3
Ross Island	77°49'S	166°43'E	160	200	-18	10-20	<3	10-60	3
Ross Island	77°38'S	166°25'E	~5	200	-18	40-80	2.3-4.3	--	3
Cape Royds	77°32'S	166°10'E	~20	200	-18	29	3-10	10-12	10
Kar Plateau	77°55'S	162°28'E	600	119	-18	7-10	2.6-4.7	6.1-9.0	11
Hobbs Glacier	77°55'S	164°29'E	~100	~188	-18	10-20	--	--	3
Marble Point	77°25'S	163°41'E	5-120	~188	-18	24-65	<1-10	1-77	12,13
Maritime East Antarctica									
Molodezhnaya	67°40'S	45°51'E	40	650	-10.8	100-150	1-28	--(ice cement)	14
Antarctic islands									
Signy Island	60°43'S	45°38'W	30-200	400	-4.4	40-130	5.6-21	16-20	15

**Values reported on a gravimetric basis.
* Dry permafrost.
References: 1 = Matsuoka et al., 1990; 2 = Berg and Black, 1966; 3 = Black, 1973; 4 = Ugolini et al., 1973; 5 = Campbell et al., submitted; 6 = Gibson et al., 1983; 7 = Ugolini and Bull, 1965; 8 = Cameron et al., 1970; 9 = Cameron, 1972; 10 = Ugolini and Grier, 1969; 11 = Ugolini, 1977; 12 = Campbell et al., 1994; 13 = Balks et al., 1995; 14 = MacNamara, 1969; 15 = Chambers, 1966.

collected during the Dry Valley Drilling Project, dry permafrost ranges from a few decimeters to a maximum of about 5 m in thickness (McGinnis et al., 1973; McGinnis, 1981). We (JGB) have dug soil pits in the dry valleys to a depth of 2.5 m without encountering ice-cemented permfrost; soil temperatures at these depths generally were -16°C or colder and estimated mean annual precipitation was <100 mm.

Geographic Distribution of Dry Permafrost

Dry permafrost occurs throughout the dry valleys of the Trans-Antarctic Mountains in south Victoria Land, especially at elevations below 900 m (Cameron, 1969). Dry permafrost is absent at higher elevations where the ablation is low and in sediments adjacent to alpine and piedmont glaciers where recharge from snowmelt occurs. Ice-cemented permafrost exists below dry permafrost to depths approaching 1,000 m (Cartwright et al., 1974; Decker and Bucher, 1977). However, permafrost is absent below much of the East Antarctic ice sheet due to the pressure of the overriding ice which initiates basal melting (see Bockheim, 1995). Permafrost also does not exist beneath thermally stratified lakes such as Lake Vanda or Don Juan Pond because of the freezing point depression due to abundant salts (Cartwright et al., 1974).

There is some question as to whether or not dry permafrost occurs in the High Arctic. There are reports of "dry frost" in well-drained soils of Inglefield Land, northeastern Greenland (Tedrow, 1970), Prince Patrick and Ellef Ringnes Islands (Tedrow, 1966; Tedrow et al., 1968; Everett, 1968), and Banks Island (Tedrow and Douglas, 1964) (Table 1). Whereas Holocene soils in coastal areas of Baffin Island have ice-cemented permafrost in the upper 50 cm, soils on mid-Foxe to early Foxe moraines (ca. 40,000 to 115,000 yr BP) on Baffin Island lack ice-cemented permafrost in the upper 110 cm (Birkeland, 1978; Bockheim, 1979; Evans and Cameron, 1979). Without confirming temperature data, it is impossible to determine whether these conditions represent dry permafrost or an unusually deep active layer. However, we (CT) have observed ice-cemented permafrost throughout the Canadian Arctic.

There are reports of dry permafrost in central Yakutia, Russia where the mean annual precipitation is <200 mm yr^{-1} and the mean annual air temperature is -10°C to -17°C (Vtiurin, 1973; Sokolov et al., 1974; 1976; Bigl, 1985). According to a map compiled by Bigl (1985), the upper 50 m of permafrost within the region bounded by 130° and 180°E longitudes and 60° and 66°N latitudes contains from 1 to 3% visible ice (Bigl, 1985). However, these areas often are underlain by highly fractured bedrock. In the driest places of central Yakutia, especially the valleys, permafrost in unconsolidated sediments is unusually ice-rich (Yershov, 1989a,b).

Dry permafrost has been reported in the arid mountains of middle Asia, including the eastern Pamirs (38°N, 72°E), the western Kunlun Mountains (36°N, 94°E), and the Ali Mountains (32°N, 73°E); the mean annual precipitation in these regions is between 25 and 100 mm (Gorbunov, 1990). According to Sveshnikova (1962; cited in Gorbunov, 1990), the moisture content of the active layer is usually 1 to 3% by weight. However, as in the case of central Yakutia, these cold-arid mountains may have an unusually deep active layer because of coarse-textured materials and high energy inputs during the summer.

Therefore, on a global basis, dry permafrost may be restricted to the dry valleys of the Trans-Antarctic Mountains.

Factors Influencing the Distribution of Dry Permafrost

The dominant factor influencing the distribution of dry permafrost appears to be climate, including mean annual precipitation and the ratio of precipitation to evaporation. The areas where dry permafrost occurs have less than 100 mm yr^{-1} of precipitation, and evaporation exceeds precipitation during the frost-free season. For example, in the Lake Vanda region of Antarctica (77°31'S, 161°40'E), the mean annual precipitation is less than 50 mm yr^{-1}, and the evaporation rate is 340 mm yr^{-1} (Harris and Cartwright, 1981).

Dry permafrost is favored by coarse-textured materials that readily release moisture to the atmosphere via evaporation or sublimation. Most of the sediments containing dry permafrost in Antarctica are loamy sands and sands with a large component (usually 50 to 90%) of coarse fragments. But it should be emphasized that coarse-textured materials have a high thermal conductivity and it would be easy to confuse dry permafrost with a deep active layer.

Age of the geomorphic surface plays an important role in the distibution of dry permafrost. Ice-cemented permafrost occurs within 50 cm of the surface in soils that are ≤18,000 yr in Antarctica (Fig. 1). However, ice cement is rarely found in the upper 100 cm in soils that are ≥90,000 yr, except at high elevations along the polar plateau. In subxerous soils along the coast where recharge from snowmelt occurs, ice cement is maintained at a depth of 35 cm for periods of 1.6-2.7 million yr (Pastor and Bockheim, 1981).

In cold deserts of Antarctica, human disturbance may initiate the formation of dry permafrost. Campbell et al. (1994) reported lower moisture contents in the upper permafrost on disturbed sites (39% by volume) than on undisturbed sites (up to 80% by volume) in the McMurdo Sound region.

Genesis of Dry Permafrost

Because of the paucity of information on dry permafrost, we can only speculate on the origin of these materials. In the dry valleys of Antarctica, dry permafrost occurs in materials deposited by dry-based glaciers that were frozen to their bed. The high ice content of these materials, normally 10 to 50% by volume (Table 2), implies that they were often saturated or supersaturated, i.e., contain excess ice.

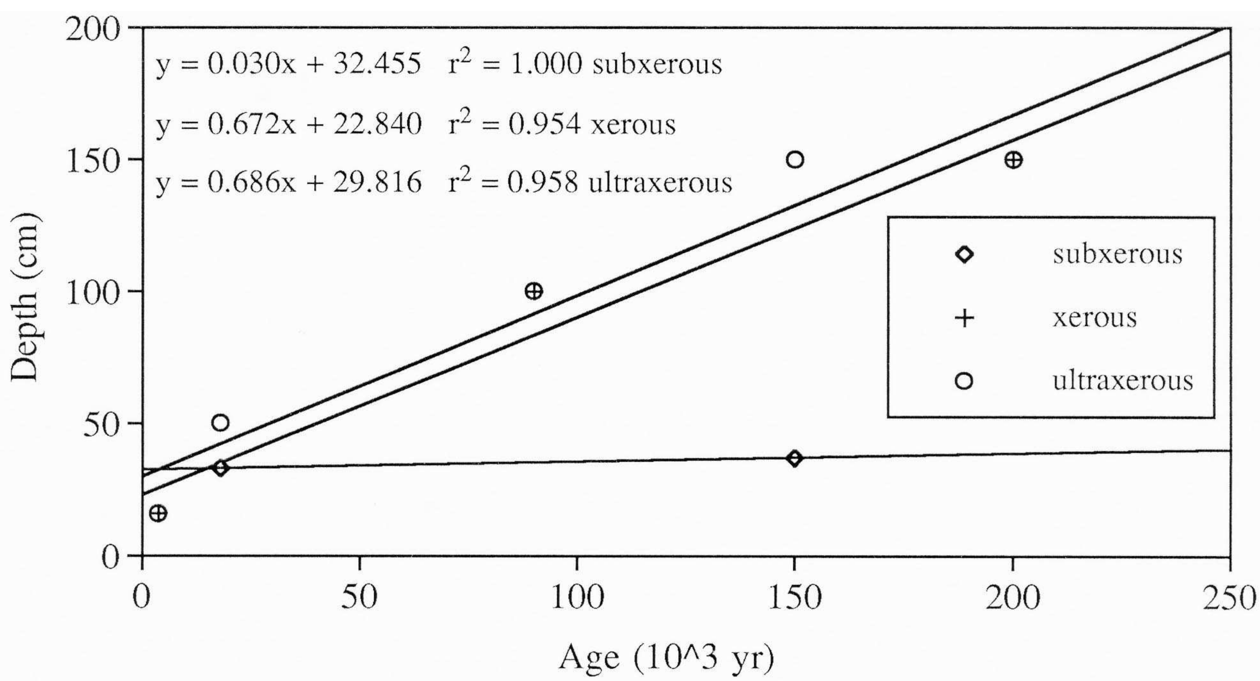

Figure 1. Relation of depth to ice cement to age of geomorphic surface for subxerous, xerous, and ultraxerous soils in the dry valleys of Antarctica (data from Bockheim and Wilson, 1992).

Table 3. Indicators of ice-cemented permafrost

Indicator	Ice-cemented permafrost	Dry permafrost
Active patterned ground	yes	no
Presence of ice wedges	yes	no
Presence of sand wedges	yes	no
Active frost cracks	yes	no
Frost heave	yes	no
Presence of cryoturbation	yes	no
Presence of cryogenic micro-structure	yes	no

The fact that dry permafrost only occurs in older sediments suggests that this interstitial ice evaporates or sublimes over time in the cold-arid environment in which evaporation exceeds precipitation (Berg and Black, 1963; Ugolini, 1964; Ugolini and Bull, 1965). Black and Berg (1963) measured a net transfer of moisture from the ice-cemented layer to the atmosphere so that the thickness of the overlying mantle increased with time. From these data, Ugolini and Bull (1965) proposed that the oldest soils, with the deepest ice-cemented layer, should be the driest. A main question raised for cold desert soils is how salts are able to move in view of the cold temperatures and arid conditions. Using radioisotopic tracers, Ugolini and Anderson (1973) showed that Na and Cl were able to move in unfrozen films of water held at high tensions on soil colloids.

INDICATORS OF DRY PERMAFROST

Unlike ice-cemented permafrost, there are no apparent indicators of dry permafrost (Table 3). In Antarctica, landscapes with dry permafrost may contain inactive patterned ground and fossil ice- and sand-wedge casts (Black and Berg, 1963; Ugolini et al., 1973). In the Trans-Antarctic Mountains, the active layer is less than 1 m in thickness and any material at or below this depth that is not cemented is very likely to be dry permafrost. Otherwise, dry permafrost can only be distinguished from a deep active layer by monitoring temperature of the sediments successively for 2 or more years.

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