Géographie physique et Quaternaire

Permafrost Distribution in Peatlands of West-Central Canada During the Holocene Warm Period 6000 Years BP

La répartition du pergélisol dans les tourbières du centre-ouest du Canada il y a 6000 ans, au cours de la période chaude de l'Holocène

Permafrost-Verteilung in Torfmooren von Zentral-West-Kanada während der warmen Holozän-Periode vor 6000 Jahren

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Résumé de l'article

Des carottes ont été prélevées dans 161 sites de tourbières pergélisolées et la composition floristique de la tourbe a été déterminée à partir de l'analyse macrofossile. Les paléoenvironnements ainsi reconstitués ont servi à révéler la présence ou l'absence de pergélisol au moment de la formation de la tourbe. La chronologie a été établie par radiodatation des changements majeurs survenus dans les séquences de tourbe et par datation des dépôts de la tourbe basale. La formation des tourbières a commencé après la disparition des glaciers de la région. Les macrofossiles démontrent que la plupart des tourbières étaient de nature minérotrophe et non pergélisolées à 6 ka, sauf dans le Grand Nord. Le pergélisol était déjà présent dans beaucoup de secteurs de l'Arctique et l'accumulation de la tourbe s'est faite concurremment avec la formation du pergélisol. Dans la partie méridionale, le développement du pergélisol dans les tourbières a commencé vers 4 ka, à la fin de la période chaude de l'Holocène moyen. Le développement du pergélisol dans les tourbières minérotrophes était associé à la prédominance de Sphagnum en surface, suscitée par l'avènement d'un climat plus froid et plus humide. L'isolation procurée par la couche de tourbe en surface et par la couverture d'arbres qui lui était associée a entraîné le développement de petites lentilles de pergélisol qui ont évolué par coalescence en grands ensembles en accord avec les conditions climatiques qui prévalaient. À 6 ka, le pergélisol était présent dans certaines tourbières, mais la zone de répartition était de 300 à 500 km plus au nord que maintenant. On estime que la température devait être de 5°C plus chaude qu'actuellement.

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PERMAFROST DISTRIBUTION IN PEATLANDS OF WEST-CENTRAL CANADA DURING THE HOLOCENE WARM PERIOD 6000 YEARS BP

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ABSTRACT The extent and distribution of permafrost in peatlands 6000 years ago was investigated in the present discontinuous and continuous permafrost zones of west-central Canada. Permafrost peatlands were cored at 161 locations and the floristic composition of the peat was determined from macrofossil analysis. The reconstructed paleoenvironments were used to indicate the presence or absence of permafrost at the time of peat formation. Chronological control was provided by radiocarbon dating of substantial changes in the peat sequences and by dates of basal peat deposits. Peatland formation began after glacial ice disappeared from the land surface of west-central Canada. Macrofossils indicate that most peatlands were fens without permafrost at 6 ka, except in the far north. Permafrost was already present in many areas of the Arctic, and peat accumulation occurred under permafrost conditions. In the southern area, permafrost development in peatlands began about 4 ka as the middle Holocene warm period came to a close. Permafrost development in the fens was associated with the development of a *Sphagnum*-dominated surface on the fens, caused by the onset of a cooler and moister climate. The insulation provided by the surface peat layer and by the associated tree cover initiated permafrost development in small lenses that coalesced into large permafrost bodies according to the prevailing climatic conditions. At the target date, 6 ka, permafrost was present in some peatlands, but the distribution zones shifted 300 to 500 km to the north, relative to the present zonation. It is estimated that this corresponds to a mean annual temperature that was about 5°C warmer than at present.

RÉSUMÉ *La répartition du pergélisol dans les tourbières du centre-ouest du Canada il y a 6000 ans, au cours de la période chaude de l'Holocène.* Des carottes ont été prélevées dans 161 sites de tourbières pergélisolées et la composition floristique de la tourbe a été déterminée à partir de l'analyse macrofossile. Les paléoenvironnements ainsi reconstitués ont servi à révéler la présence ou l'absence de pergélisol au moment de la formation de la tourbe. La chronologie a été établie par radiodatation des changements majeurs survenus dans les séquences de tourbe et par datation des dépôts de la tourbe basale. La formation des tourbières a commencé après la disparition des glaciers de la région. Les macrofossiles démontrent que la plupart des tourbières étaient de nature minérotrophe et non pergélisolées à 6 ka, sauf dans le Grand Nord. Le pergélisol était déjà présent dans beaucoup de secteurs de l'Arctique et l'accumulation de la tourbe s'est faite concurremment avec la formation du pergélisol. Dans la partie méridionale, le développement du pergélisol dans les tourbières a commencé vers 4 ka, à la fin de la période chaude de l'Holocène moyen. Le développement du pergélisol dans les tourbières minérotrophes était associé à la prédominance de *Sphagnum* en surface, suscitée par l'avènement d'un climat plus froid et plus humide. L'isolation procurée par la couche de tourbe en surface et par la couverture d'arbres qui lui était associée a entraîné le développement de petites lentilles de pergélisol qui ont évolué par coalescence en grands ensembles en accord avec les conditions climatiques qui prévalaient. À 6 ka, le pergélisol était présent dans certaines tourbières, mais la zone de répartition était de 300 à 500 km plus au nord que maintenant. On estime que la température devait être de 5°C plus chaude qu'actuellement.

ZUSAMMENFASSUNG *Permafrost-Verteilung in Torfmooren von Zentral-West-Kanada während der warmen Holozän-Periode vor 6000 Jahren.* Die Ausdehnung und Verteilung von Permafrost in Torfmooren vor 6000 Jahren wurden in den heutigen diskontinuierlichen und kontinuierlichen Permafrost-Zonen von Zentral-West-Kanada untersucht. An 161 Plätzen hat man Kernbohrungen in den Permafrost-Torfmooren durchgeführt und mittels der makrofossilen Analyse die Flora-Kompositon des Torfs bestimmt. Man erhielt eine chronologische Kontrolle mittels Radiokarbondatierung von gewichtigen Veränderungen in den Torfsequenzen und mittels der Daten von Torfablagerungen an der Basis. Die Torfbildung begann, nachdem das glaziale Eis von der Landoberfläche von Zentral-West-Kanada verschwunden war. Die Makrofossile zeigen, daß die meisten Torfmoore um 6 ka Moore ohne Permafrost waren, außer im hohen Norden. Permafrost gab es schon in vielen Gebieten der Arktis, und die Torfakkumulation geschah unter Permafrost-Bedingungen. Im südlichen Teil begann die Permafrost-Entwicklung in den Torfmooren um etwa 4 ka, als die mittlere warme Holozän-Periode dem Ende zuging. Die Permafrost-Entwicklung in den Mooren war mit der Entwicklung einer von Sphagnum dominierten Oberfläche der Moore verbunden, hervorgerufen durch den Beginn eines kühleren und feuchteren Klimas. Die Isolierung, die durch die Oberflächenschicht und durch die damit verbundene Baumbedeckung hervorgerufen wurde, erzeugte Permafrost-Entwicklung in kleinen Linsen, welche sich zu breiten Permafrost-Einheiten vereinigten, entsprechend den vorherrschenden klimatischen Bedingungen. Um 6 ka gab es Permafrost in einigen Torfmooren, aber die Verteilungszonen waren 300 bis 500 km nördlicher als heute. Man schätzt, daß dies einer durch-schnittlichen Jahrestemperatur entspricht, die um etwa 5°C wärmer als heute war.

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INTRODUCTION

Paleoecological studies and climatic reconstructions showed that the general warm period that followed the disappearance of glacial ice from North America continued well into the middle Holocene (COHMAP Members, 1988). This warm, dry period, often referred to as the Hypsithermal (altithermal, xerothermic, thermal maximum, Deevey and Flint, 1957), began about 10 ka ('000 years before present) in western Canada and peaked from 9 to 6 ka in the Great Plains (Anderson *et al.*, 1989). In the continental parts of North America and Eurasia the summer temperatures at 6 ka were 2 to 4°C higher than at present (COHMAP Members, 1988). These temperatures influenced the formation of postglacial peatlands and the development of permafrost in the peatlands.

The present distribution of permafrost shows a latitudinal zonation where the incidence and thickness of permafrost increases with latitude. Although there were numerous attempts at delineating and naming these zones, no consensus has been reached (Nelson, 1989). The following zones are described in terms of permafrost development in peatlands (Fig. 1). At the most southerly extent, permafrost occurs as small, isolated lenses in peat (Zoltai, 1972) that reach into the mineral substrate only under palsas. This has been named the *Localized Permafrost Zone* (LPZ, Zoltai, 1971). Farther north the permafrost lenses occur more frequently in bogs or as isolated islands in minerotrophic fens, but unfrozen peatlands are still more extensive than peatlands with permafrost (*Sporadic Permafrost Zone*, SPZ). Here, permafrost usually reaches the mineral soil beneath both the peat plateaus and palsas. Still farther north in the *Widespread Permafrost Zone,* (WPZ), most peatlands contain permafrost, but many fens and all shallow lakes are free of permafrost. The most northerly region is within the *Continuous Permafrost Zone*, (CPZ) where all land surfaces and even shallow water bodies are underlain by permafrost.

The generally parallel latitudinal zonation suggests a relationship to climate. The mean annual temperature in the LPZ is between 0 and −1°C (Vitt *et al.*, 1994), and in the SPZ it is between −1 and −5.5°C (Brown, 1978). In the WPZ the mean annual temperature is generally between −5.5 and −8.3°C (Nelson, 1989); in the CPZ the mean annual temperature is lower than −8.3°C. It is recognized, however, that the development of permafrost in peatlands is also influenced by other factors, such as timing and amount of snowfall, annual precipitation and the presence of peatlands that are susceptible to permafrost development.

Previous research has established the dynamics of permafrost development in peatlands (Zoltai, 1972; Zoltai and Tarnocai, 1975; Payette *et al.*, 1976; Couillard and Payette, 1985; Seppälä, 1988). It was found that in the present LPZ, SPZ and WPZ areas, most of the permafrost developed in non-frozen peatlands. Macrofossil analyses of the peat showed that most of the peat was deposited in a non-permafrost environment, and permafrost development followed later. The events leading to permafrost aggradation may have been in direct response to a change in climate, or it may have been an indirect response to a cooler and moister climate that led to the development of *Sphagnum*-dominated peatlands.

Observations in the discontinuous permafrost zone show that permafrost formation is initiated in peatlands mainly as particular conditions are created by the vegetation. The most common sequence is where small *Sphagnum* cushions develop on the surface of fens (Zoltai and Tarnocai, 1975). These cushions, projecting above the water table, insulate the seasonal frost against rapid summer thawing. Eventually a small lens of frost fails to thaw under the cushion and becomes permafrost. As this frost lens thickens, the water in the peat changes to ice, further elevating the surface above the water table and increasing its insulation value. Small trees often become established on the cushions, intercepting some of the snow and thus reducing the insulation effect of the snow layer. This process, which eventually reaches an equilibrium with the prevailing climate, appears to be the main mechanism of permafrost initiation in the SPZ and WPZ.

A second mechanism for the initiation of permafrost is also prevalent, mainly in the LPZ (Zoltai, 1972). Here local patches (several square metres) of dense tree growth can develop in large bogs, or as small islands in fens. The dense tree canopy (*Picea mariana*) intercepts much of the snow, resulting in a much reduced snow cover under the trees (Zoltai and Tarnocai, 1971). Without a thick insulating snow blanket, increased heat loss occurs during the winter, causing frost to penetrate deeper under the dense tree cover. Some of the seasonal frost may fail to thaw completely during the summer and hence becomes permafrost. Initially the permafrost consists only of thin frozen layers, but these can consolidate into larger lenses as the surface is elevated by the freezing of the water (Zoltai, 1972). This in turn creates drier surface conditions, further promoting dense tree growth and less snow cover on the surface, enhancing further permafrost accretion.

Isolated permafrost bodies have been observed in wetlands that have only a thin peat layer (Brown, 1980; Seppälä, 1980; Tarnocai, 1982), and their internal stratigraphy does not suggest any relationship to peatland dynamics. No mechanism has been suggested for their formation, but one can speculate that local frost heaving in the underlying mineral soil can raise the surface sufficiently above the water table to allow the desiccation of the peat layer, hence creating an insulating layer (Seppälä, 1988).

Various permafrost mounds (Outcalt and Nelson, 1984; Pollard and French, 1983) and frost blisters (Van Everdingen, 1982) that may be present in some wet areas are formed by the injection of ice between the permafrost table and the freezing surface layer. The genesis of these forms is, however, not relevant to permafrost initiation and development in peatlands, and they are not considered here.

In this paper the extent and timing of permafrost development in peatlands of west-central Canada are examined.

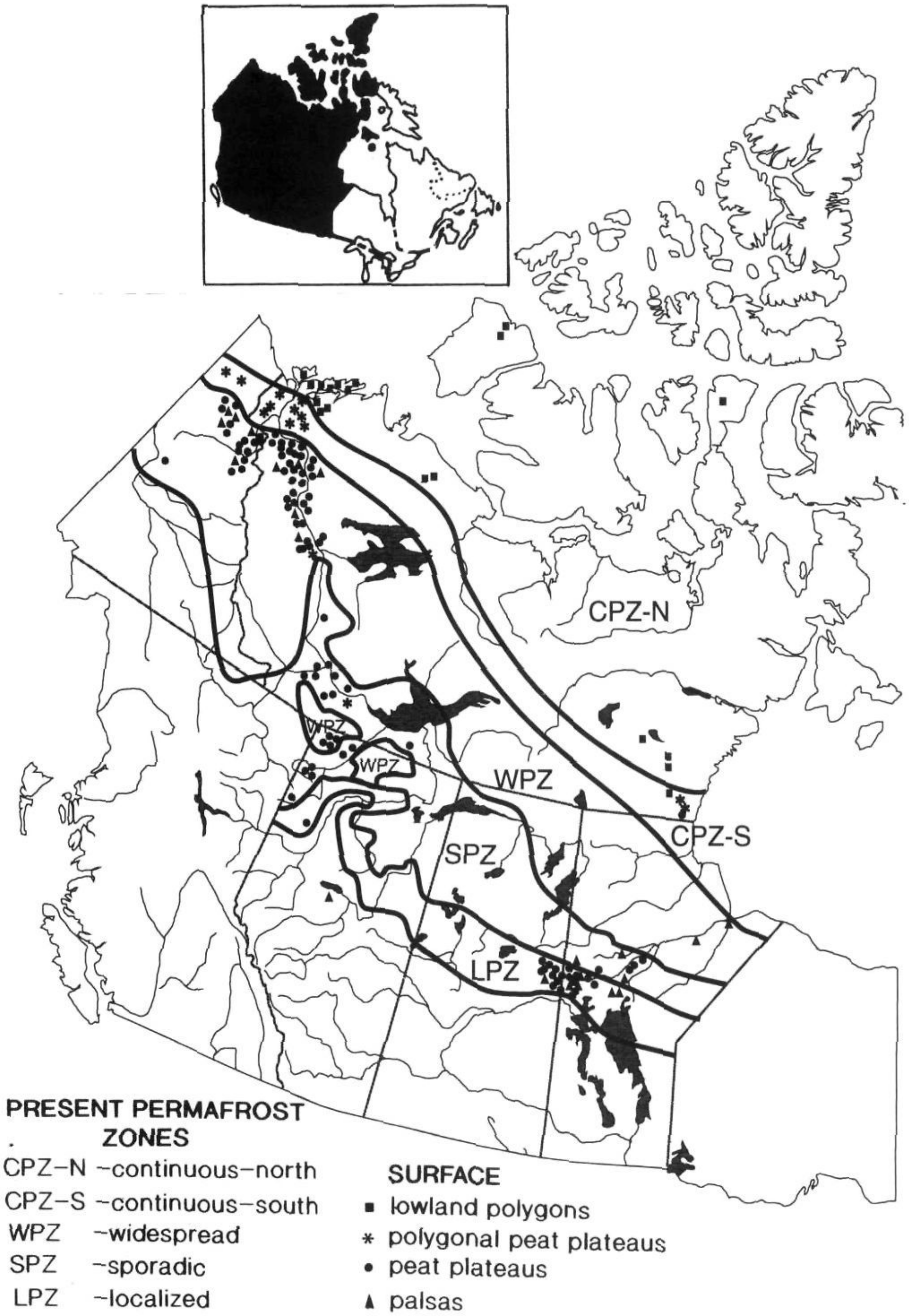

FIGURE 1. Permafrost zones at present, based on permafrost distribution in peatlands, with locations of peatland study sites.

Zones de pergélisol actuelles, à partir de la répartition du pergélisol dans les tourbières et localisation des sites de tourbières étudiées.

An estimate of permafrost distribution in peatlands during the Holocene warm period is presented for the target date of 6 ka.

STUDY AREA

The data base consists of field information obtained by coring and sampling of peatlands in west-central Canada during the past 23 years. Parts of this information have been published (Zoltai, 1972; Zoltai and Tarnocai, 1975; Zoltai, 1993), although much is still unpublished. In the LPZ, 30 sites have been examined, mainly in Saskatchewan and Manitoba. In the SPZ, 26 sites were located, in Manitoba, Alberta, and the Northwest Territories. The WPZ was represented by 71 sites (98 cores), mainly from the Mackenzie Valley in the Northwest Territories, but also including sites from Yukon, Alberta, and Manitoba. In the CPZ, 34 sites (52 cores) were located. The permafrost peat landforms examined were palsas (30) and peat plateaus (95) in the LPZ, SPZ and WPZ, and polygonal peat plateaus (13 sites), low centre (3) and high centre polygons (16).

METHODS

Coring sites were selected generally on the highest parts of palsas, or at the centres of peat plateaus. In large peat plateaus, the coring locations were at least 20 m from the edge of the plateau. At the selected sites small excavations were made to sample the peat of the active layer. The permafrost was sampled with a small diameter permafrost probe (Zoltai, 1978) until mineral soil was reached, or until at least one metre of clear ice was penetrated. Whenever possible, the adjacent unfrozen peat was cored with a Macauley peat sampler; samples were taken at 10-cm intervals. At some locations where peat sections were exposed by erosion, the peat face was cut back at least 15 cm to expose uncontaminated materials and the regular sampling procedure was followed.

In the laboratory, the samples were examined to determine the main components of the peat. When possible, distinctions were made between *Sphagnum* species growing in wet and drier habitats. The samples were further analysed to determine their chemical and physical characteristics.

The peat samples were grouped on the basis of their composition into the following general groups indicating broad environmental conditions.

SPHAGNUM-DOMINATED BOGS AND POOR FEN PEATLANDS

Sphagnum peat — Peat composed dominantly of *Sphagnum fuscum* remains, but often including *S. magellanicum* and *S. angustifolium*. Ericaceous shrub twiglets and roots are often present. Conifer (mainly *Picea mariana*) needles, cones, or twiglets may be present. This peat is generally well preserved because it usually occurs near the surface.

Woody *Sphagnum* peat — Peat consisting mainly of ericaceous shrub stems, roots and leaves, with variable amounts of *Sphagnum fuscum*, and rarely, lichen (*Cladina* sp.) remains. The peat is slightly to moderately decomposed.

FORESTED PEATLANDS

Sylvic (forest) peat — Peat consisting of well decomposed woody material, rootlets, and needles. On occasion feather moss remnants (mainly *Hypnum* sp., *Pleurozium* sp., *Hylocomium* sp.) can be identified.

FEN PEATLANDS

Sedge-moss peat — Peat composed of remnants (roots, leaves) of *Carex* spp. and brown mosses (*Drepanocladus* spp., *Campylium* spp., *Scorpidium* sp., often with various amounts of fragments of wood, twiglets and woody rootlets. The peat is moderately to well decomposed.

Humic peat — Peat consisting of well-decomposed organic matter, where the constituents are usually no longer recognizable.

RESULTS

The results of the analysis show that nearly all permafrost peatlands are covered by a thin surface layer of peat that differs in origin from the underlying fen peat (Table I). This surface layer is the thickest in the south and decreases gradually towards the north.

The surface peat material varies among the various permafrost zones, according to the regional vegetation development of the permafrost peatlands. Well-decomposed sylvic peat is prevalent in the LPZ under densely forested peat plateaus and palsas. In the SPZ where open canopied black spruce with *Sphagnum fuscum*, some ground lichens and Labrador tea (*Ledum groenlandicum*) form the vegetation cover; *Sphagnum* or woody *Sphagnum* peat is most common. In the WPZ the same species are present, but with fewer, stunted trees. The ground cover is lichen (mainly *Cladina mitis, C. rangiferina, C. stellaris*) and Labrador tea, with *Sphagnum* mosses in moister depressions. The lichen is usually not represented in the peat, leaving ericaceous shrub debris and *Sphagnum* remains as the main peat constituents.

Along the southern fringe of the CPZ, (CPZ-S) the peatlands are covered with lichen (*Cetraria nivalis, C. cucullata, Alectoria* spp.), with *Sphagnum fuscum* in the moister areas. In this area the surface *Sphagnum* layer is underlain by more *Sphagnum* peat at six of the sites. In such cases the surface layer was determined by the greater degree of decomposition observed, compared to that in the underlying *Sphagnum* peat. Nearly all peatlands occur in lowland polygons (Zoltai and Tarnocai, 1975), either in low-

TABLE I

Number of sites with different surface materials, and the average thickness of surface layer above fen peat (with standard error) in various permafrost zones

Zone	Sites/Cores	Sylvic		*Sphagnum*		Woody *Sphagnum*		Sedge-moss	Humic	
		n	cm	n	cm	n	cm	n	n	cm
LPZ	30/30	27	55.8±3.1	2	80.0±14.1	–	–	1	–	–
SPZ	27/27	5	50.6±2.3	21	56.5±4.6	–	–	1	–	–
WPZ	71/98	5	51.6±6.4	65	42.7±5.3	22	33.0±7.0	6	–	–
CPZ-S	14/29	1	39	28	44.9±8.4	–	–	–	–	–
CPZ-N	20/23	–	–	5	43.0±10.7	–	–	–	18	30.5±1.7

centre forms with wet centres or in high-centre forms which have domed, well drained centres. Low-centre polygons are common in the northern CPZ (CPZ-N), with only thin peat development. Here, most peaty high-centre polygons have a bare surface, where the peat is oxidizing. The surface peat usually consists of highly humified organic material.

In most permafrost zones there are only a very few permafrost peatlands with fen peat at the surface. These are generally on the margins of peat plateaus and were probably affected by permafrost as the main permafrost body developed. Only in two peatlands did the permafrost appear to have originated in the fens.

CHRONOLOGY

Published radiocarbon dates of basal peat deposits were collected from 117 locations within the permafrost zones. Only those dates were included that were obtained from peat of fen deposits; those from lacustrine organic sediments were not included. In addition, basal dates from well-decomposed (humic) peat of uncertain origin often found in the Arctic were included. The basal dates are shown in Figure 2 as being older or younger than 6 ka.

Radiocarbon dates have been obtained from the top of the fen peat sequence, immediately below the surface *Sphagnum* layer, from permafrost peatlands in the discontinuous (WPZ, SPZ and LPZ) permafrost zones (Table II). These dates show that the earliest development of the *Sphagnum* cap was about 3.7 ka, and that it continued since then at various locations. The dates appear to indicate that the *Sphagnum* cap developed earlier in the SPZ than in the more northerly WPZ.

In the southern fringe of the CPZ the transition between the decomposed surface layer and the underlying *Sphag-*

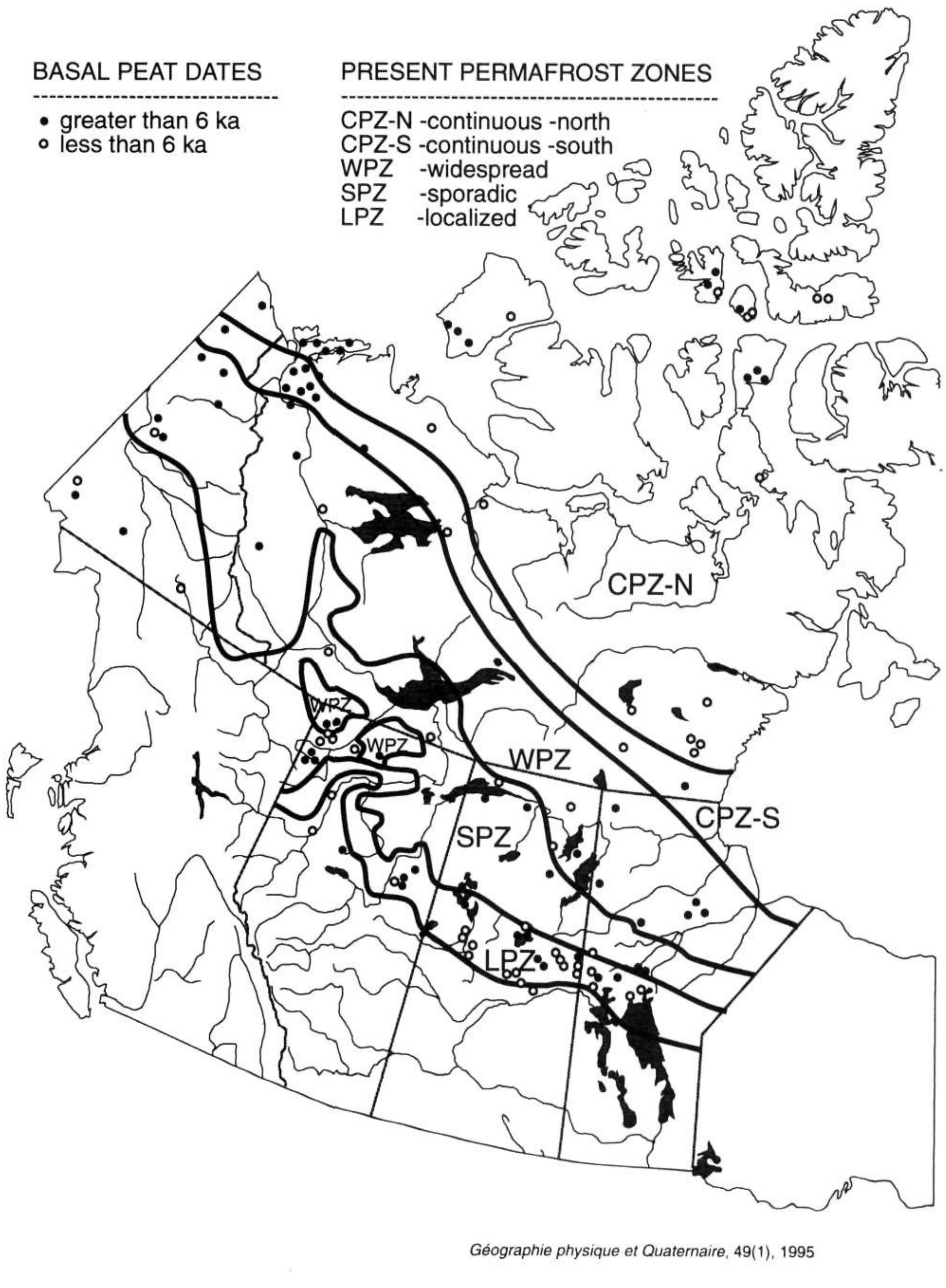

FIGURE 2. Basal peat dates in the present permafrost zones, showing older than 6 ka and younger that 6 ka dates.

Datations de tourbe basale dans les zones de pergélisol actuelles selon qu'elles sont plus vieilles ou plus jeunes que 6 ka.

num or fen peat was dated between 5.8 and 0.5 ka (Table III), a similar spread of dates to that in the discontinuous permafrost zones. The dates of the thicker *Sphagnum* deposits indicate that bog conditions were established between 6.6 and 4.7 ka in this area.

In the northern CPZ there appear to be several groups of peatland dates. One group shows basal dates in the 6.0 to 10.1 ka range (Table IV, Nos. 1 to 5). The surface dates of these peatlands are also old, in the 5.0 to 8.0 ka range. Other basal dates are younger (Table IV, Nos. 10 to 16), dominantly in the 4.0 to 5.0 ka range with relatively recent surface dates, in the 2.0 to 3.0 ka range. The remaining dates are intermediate (Table IV, Nos. 6 to 9), with relatively old basal dates (6.0 to 8.0 ka), although the surface peat is in the 1.0 to 3.0 ka range.

DISCUSSION

The trend of regional development of peatlands in the continental boreal region (including the LPZ, SPZ, and WPZ) shows that initial peatland development proceeds to form fens on mineral soil in poorly drained areas (paludification) or over ponds (terrestrialization). At a later stage, *Sphagnum*-dominated fens may be established in parts of the fens that may proceed to develop into bogs when the surface is no longer influenced by the water table of the fen (Zoltai and Johnson, 1985; Nicholson and Vitt, 1990; Kuhry *et al.*, 1992). In addition to local water quality conditions, the development of bogs is limited by climate. Few bogs are formed if the summer precipitation is lower than 250 mm and the mean annual temperature is above 2°C (Vitt *et al.*, 1994).

TABLE II

Radiocarbon dates at the change from fen peat to Sphagnum peat in the discontinuous permafrost zones (WPZ, SPZ, LPZ)

Zone	Location	Depth (cm)	Date	Lab No.	Source
1. WPZ	68°26'N 133°52'W	27-29	530±120	AECV 974C	This paper
2. WPZ	67°30'N 133°46'W	41-46	670±100	AECV 972C	This paper
3. WPZ	67°28'N 134°40'W	42-46	1980±200	AECV 976C	This paper
4. WPZ	67°28'N 134°35'W	98-104	1720±100	AECV 977C	This paper
5. WPZ	67°25'N 134°18'W	59-62	1660±110	AECV 975C	This paper
6. SPZ	61°28'N 120°55'W	155	3000	WAT-400	Chatwin 1983
7. SPZ	60°03'N 112°54'W	67-70	2870±90	AECV 993C	This paper
8. SPZ	59°07'N 118°08'W	109-113	2410±120	AECV 985C	Zoltai, 1993
9. SPZ	58°18'N 119°17'W	83-86	2710±100	AECV 990C	Zoltai, 1993
10. LPZ	54°36'N 101°26'W	84-90	1200±100	BGS 863	This paper

TABLE III

Radiocarbon dates of peat from polygonal peat plateaus of the southern continuous permafrost zone (CPZ-S)

Location	Depth (cm)	Stratigraphy	Date	Lab. No.	Source
1. 68°22'N 132°42'W	50-60	*Sphagnum*/wood	5420±70	WIS-279	Dyck & Fyles, 1963
	360-366	wood/mineral	8200±300	GSC-25	Dyck & Fyles, 1963
2. 67°49'N 139°50'W	21.5-24.5	humic/*Sphagnum*	3025±85	S-1865	Ovenden,1982
	175-178	sedge/lacustrine	10080±340	S-1871	Ovenden, 1982
3. 67°41'N 132°05'W	27-32	*Sphagnum*/sedge, moss	2710±60	BGS 147	Delorme & Zoltai,1984
	266-269	sedge, moss/min*	8610±100	BGS 149	Delorme & Zoltai,1984
4. 67°06'N 125°47'W	34-36	humic/*Sphagnum*	1810±60	WIS-297	Nichols, 1974
	174-176	*Sphagnum*/sedge	6630±85	WIS-299	Nichols, 1974
5. 63°04'N 110°47'W	24-26	humic/*Sphagnum*	3380±105	GaK-5050	Nichols, 1975
	160-163	sedge,moss/min	6080±150	BGS 474	This paper
	157-159	*Sphagnum*	6170±130	GSC-1840	Nichols, 1975
6. 63°01'N 128°48'W	30	peat	3000±50	GSC-3176	MacDonald, 1983
	230	humic	8640±160	GSC-3097	MacDonald, 1983
7. 61°15'N 100°57'W	4-6	humic/*Sphagnum*	870±60	GaK-5062	Nichols, 1975
	288-290	*Sphagnum*	4690±140	GSC-1781	Nichols, 1975
8. 61°15'N 100°55'W	20-22	*Sphagnum*	1510±80	WIS-88	Bender *et al.*,1966
	148-150	*Sphagnum*	5780±110	WIS-67	Bender *et al.*, 1966
9. 61°10'N 100°55'W	4-6	*Sphagnum*	630±70	WIS-133	Nichols, 1967
	108-110	*Sphagnum*	4800±90	WIS-166	Nichols, 1967
10. 61°08'N 97°06'W	13-15	humic/*Sphagnum*	1920±80	BGS-478	This paper
	135-138	sedge, moss/min	5110±130	BGS 477	This paper
11. 60°37'N 96°59'W	20-25	humic/*Sphagnum*	550±80	BGS 475	This paper

*min = mineral soil

TABLE IV

Radiocarbon dates of peat from high centre peat polygons in the northern continuous permafrost zone (CPZ-N)

Location	Depth (cm)	Stratigraphy	Date	Lab No.	Source
1. 75°45'N 98°18'W	9-12	humic/peat	1170±150	GSC-402	Lowdon *et al.*, 1967
	312-326	peat/ice	6510±150	GSC-253	Lowdon *et al.*, 1967
2. 75°40'N 97°40'W	25	humic peat	5070±60	GSC-2326	Tarnocai & Zoltai, 1988
	130	peat	6160±90	GSC-2317	Tarnocai & Zoltai, 1988
3. 73°16'N 118°50'W	15	humic/moss	2800±100	BGS 698	Tarnocai & Zoltai, 1988
	178	moss/mineral	4250±100	BGS 699	Tarnocai & Zoltai, 1988
4. 72°58'N 94°57'W	30-32	humic/sedge, moss	6070±100	BGS 337	This paper
	133-135	sedge, moss/min*	6280±80	GSC-2339	This paper
5. 72°52'N 93°37'W	0-3	humic	1320±60	GSC-2945	Blake, 1987
	225-230	peat/mineral	7590±80	GSC-2583	Blake, 1987
6. 71°56'N 123°14'W	61	humic	6940±110	GSC-10	Dyck & Fyles, 1963
	244	peat/mineral	9820±220	GSC-197	Dyck & Fyles, 1963
7. 70°07'N 93°33'W	5-8	humic	2080±60	GSC-3282	Blake,1988
	130-132	peat/mineral	4750±60	GSC-3277	Blake, 1988
8. 69°25'N 131°40'W	15	humic/moss	2920±130	GSC-1669	Lowdon & Blake, 1981
	80	moss	6770±140	GSC-1737	Lowdon & Blake,1981
9. 69°15'N 138°02'W	38-40	humic/sedge, moss	8260±110	BGS 196	This paper
	298-300	sedge, moss/min	10100±130	BGS 197	This paper
10. 69°09'N 134°17'W	58	peat	1890±60	Beta-11569	Tarnocai & Zoltai, 1988
	310	peat	4810±60	Beta-11564	Tarnocai & Zoltai, 1988
11. 69°07'N 123°56'W	20-22	humic/sedge, moss	3150±90	BGS 216	Tarnocai & Zoltai, 1988
	320-324	sedge, moss/min	6020±100	BGS 217	Tarnocai & Zoltai, 1988
12. 68°45'N 120°39'W	5-10	humic/peat	2200±80	GSC-5200	Zoltai *et al.*, 1992
	115-117	meat/mineral	4030±100	GSC-5188	Zoltai *et al.*, 1992
13. 63°39'N 95°50'W	20-22	humic/sedge, moss	2130±80	BGS 404	This paper
	150-152	sedge, moss/min	3850±400	BGS 406	This paper
14. 62°07'N 96°32'W	20-24	humic/sedge, moss	920±80	BGS 484	This paper
	202-204	sedge, moss/min	3890±160	BGS 483	This paper
15. 61°38'N 97°12'W	23-25	humic/sedge, moss	2300±100	BGS 481	This paper
	174-177	sedge, moss/min	4380±130	BGS 480	This paper

* min = mineral soil

Radiocarbon dates of basal peat show that peat deposits were widespread throughout the area at 6 ka (Fig. 2). Exceptions occurred along the southern boundary of the LPZ, where all ages are <6 ka. This observation has been attributed to lack of peatland development during an arid and warm climatic period prior to 6 ka (Zoltai and Vitt, 1990). A similar grouping of <6 ka peatlands occurs in the CPZ-S, west of Hudson Bay (Fig. 2), in an area that became free of glacial ice cover between 7 and 8 ka ago (Dyke and Prest, 1987). In general, all peatlands are <6 ka on the eastern mainland, generally east of Great Bear and Great Slave lakes, which became deglaciated later than the west.

Permafrost development in peatlands is associated with the development of bogs (SPZ and WPZ) or the initiation of *Sphagnum*-rich treed fens (LPD). In much of the discontinuous permafrost zone, however, bog or treed fen development did not take place until after 5 ka, indicating that permafrost development was also lacking prior to this date. Basal dates indicate that *Sphagnum* development and the associated permafrost development in peatlands began in the CPZ-S about 6 ka. There are indications that bog development and associated permafrost formation began earlier in the north and gradually spread southward. Within Alberta, bog development occurred earlier in the north (about 5 ka) than farther south in the present LPZ (about 2.2 ka, Zoltai and Vitt, 1990).

In the CPZ-N, the available data on the age of the surface layer appear to be contradictory. Under the present climatic regime, limited peat formation takes place in low-centre polygons, where the wetland is underlain by permafrost. Here the peaty material generally shows the effects of mixing by frost action (cryoturbation) as evidenced by the presence of mineral sand grains or stones in the peat, evident in both low and high centre polygons. The peat contains large amounts of mineral soil particles (35 to 50% by weight), as well as small stones and boulders (Zoltai *et al.*, 1992). Boulders up to 0.02 m^3 can be found embedded in the peat or on the surface underlain by peat on high centre polygons where the basin configuration excludes fluvial deposition. Frost heaving and mixing as the peat is being deposited is a likely mechanism for the distribution of mineral soil grains and stones in the peat. Such evidence of cryoturbation was seen in high-centre polygons at nine of the 20 sites cored, as well as in the shallow peat of low centre polygons, indicating that these peats were deposited in a permafrost environment.

In some areas in the CPZ-N, however, peat formation can occur in the absence of permafrost, as shown by the recent dates of surface peat. A number of high centre polygons are composed of old peat, deposited before 6000 BP in non-permafrost environments. The absence of a sufficient number of reliably dated peat sequences may well be the source of this apparent contradiction.

RECONSTRUCTION OF PALEOCLIMATE

Based on the available evidence, the following general scenario of permafrost distribution in the peatlands at about 6 ka can be generated:

1. In the approximate area of the present LPZ, the climate was warm and dry. No peatlands and no permafrost occurred in this area at 6 ka.

2. About 6 ka the dominant form of peatland in the present SPZ and southern WPZ was fen, which covered a much smaller portion of the area than at present. Permafrost was absent from these fens.

3. In the northern part of the present WPZ, small *Sphagnum*-dominated fens developed, with small permafrost lenses in some of these, similar to those found in the present LPZ.

4. In the present CPZ-S, bog development was well advanced and scattered permafrost was present in some of them, resembling the permafrost distribution in the southern SPZ of the present.

5. In the western part of the present CPZ-N, a major peat-forming period came to a close at about 6 ka. In the southern portion of this western area permafrost occurred in a large number of peatlands, in proportions that are possibly similar to the WPZ of the present.

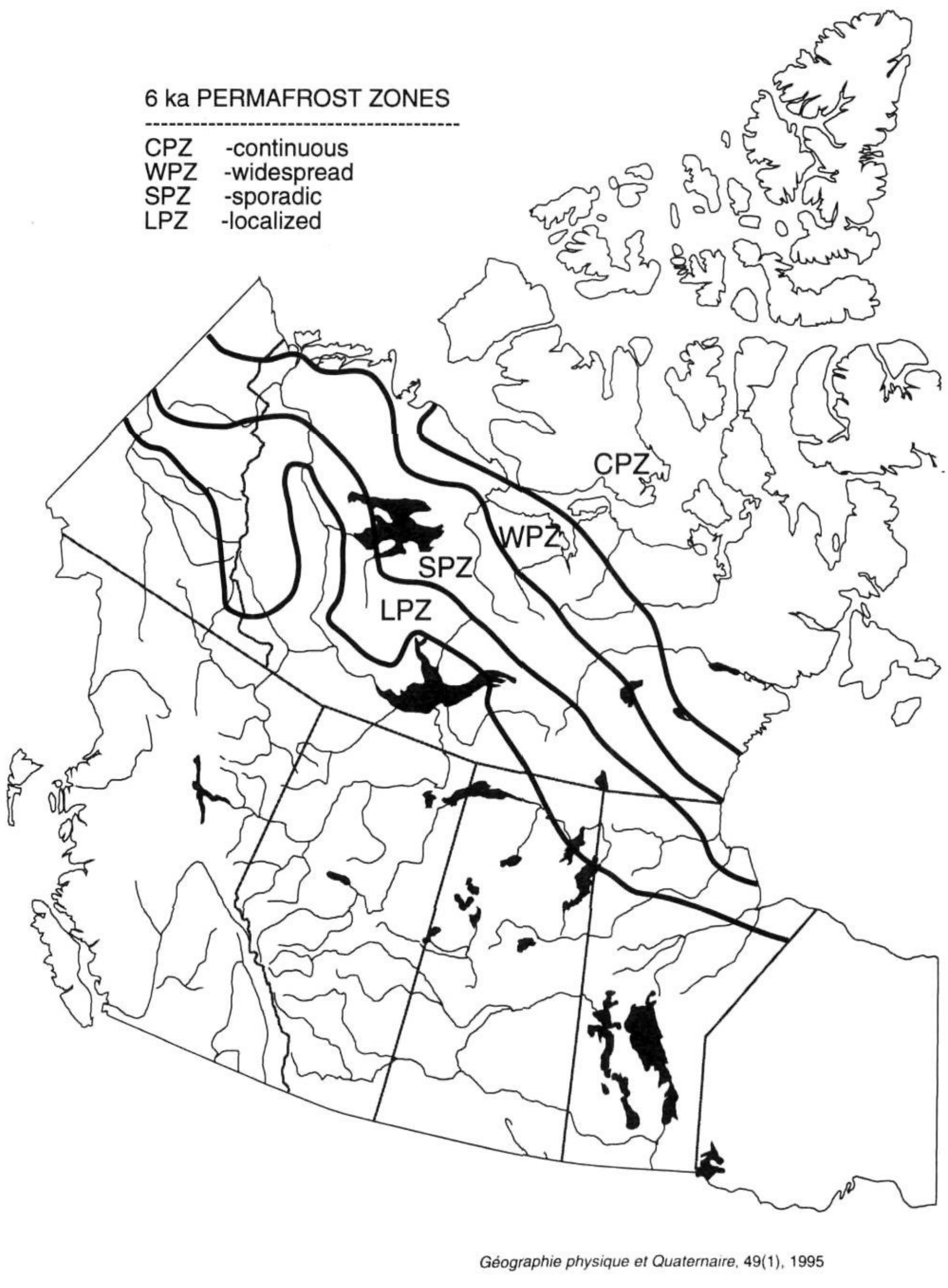

FIGURE 3. Approximate position of permafrost zones at 6 ka, based on permafrost distribution in peatlands.

Emplacement approximatif des zones de pergélisol à 6 ka, à partir de la répartition du pergélisol dans les tourbières.

6. In the mainland part of the present CPZ-N, especially near Hudson Bay, peat formation did not take place at this time.

7. In the northern portion of the present CPZ peat development occurred under permafrost conditions, but the peatlands were limited in extent.

This scenario permits the tentative reconstruction of permafrost distribution in the peatlands of west-central Canada about 6 ka (Fig. 3). This map must be regarded as an initial reconstruction because of the limited number of sites and their uneven distribution.

Further constraints are posed by the allogenic processes that create conditions under which permafrost can be generated. First, appropriate water quality and climatic conditions must be present before *Sphagnum*-dominated peatlands can form. Next, the local thermal conditions of the prevailing climate would have to be modified by the *Sphagnum*-dominated cover to initiate permafrost development. Furthermore, there is instrumented evidence of a current warming trend (1.4°C per century) in central Western Canada (Gullett, 1992). The possibility exists that the present permafrost distribution in the peatlands indicates a cooler past climate than the present. Permafrost instability in the LPZ and SPZ may be an indication that permafrost conditions are presently undergoing adjustment to a warmer climate.

The tentative map of permafrost distribution in peatlands at 6 ka shows a general displacement of the zones as compared to the present (Fig. 3). In particular, the LPZ was much farther north and more extensive than at present, approximately covering the southern half of the present area of the WPZ. The northward displacement of the CPZ was greater in the west than in the area close to Hudson Bay.

Some cautious paleoclimate implications may be drawn from the reconstructed 6 ka permafrost distribution. The mean annual temperature at the southern boundary of the present LPZ is at 0°C, but the corresponding boundary at 6 ka was at about the current –5°C isotherm. Similarly, the present boundary between the SPZ and WPZ is at about –5.5°C whereas the 6 ka boundary was at about –10 to –11°C. The southern boundary of the CPZ is close to the –8.3°C isotherm, but it was probably near the present –12°C isotherm at 6 ka. In general, the northward shift indicates that the mean annual temperatures were about 5°C warmer than at present.

A comparison of the 6 ka permafrost distribution with projected permafrost boundaries under equilibrium conditions resulting from a postulated surface temperature change of 4 to 5°C due to greenhouse climate warming (Woo *et al.*, 1992) shows comparable northward shifts. The position of the southern limit of permafrost at 6 ka was farther north in the west than in the greenhouse warming projection, although the boundaries nearly coincide east of Great Slave Lake. The position of the southern boundary of the CPZ is nearly identical in both the greenhouse warming and the 6 ka projections.

CONCLUSIONS

This paper demonstrates that a knowledge base of wetland development processes exists to make an ecologically sound estimate of the paleoclimate of permafrost dynamics at 6 ka. However, the accuracy and reliability of this reconstruction is questionable because of the uneven and incomplete data base. With the addition of carefully selected sites, much of the uncertainty could be removed and the paleoclimatic conditions responsible for the distribution of permafrost in peatlands could be determined at a continental scale from the study of peatlands. This would provide an independent test of paleoclimate reconstructions obtained from the study of vegetation or faunal ecosystems.

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