The Vault Creek Tunnel (Fairbanks Region, Alaska): A Late Quaternary Palaeoenvironmental Permafrost Record

Hanno Meyer
Alfred Wegener Institute for Polar and Marine Research, Research Unit Potsdam, Potsdam, Germany
Kenji Yoshikawa
Water and Environmental Research Center, Institute of Northern Engineering, University of Alaska Fairbanks, Alaska
Lutz Schirrmeister, Andrei Andreev
Alfred Wegener Institute for Polar and Marine Research, Research Unit Potsdam, Potsdam, Germany

Abstract

The Vault Creek (VC) gold mining tunnel north of Fairbanks, Alaska, is the deepest and longest permafrost tunnel ever made available for periglacial research. The VC tunnel sedimentary profile includes loess and fluvial gravels above bedrock and is, thus, comparable to the famous Fox permafrost tunnel. AMS ^{14}C dates from the VC tunnel indicate that loess accumulation took place around 40–50 ka BP, whereas the fluvial sediments show mostly infinite ^{14}C ages, confirmed by IRSL dates around 55–85 ka. However, the pollen record of the VC tunnel reflects very warm and unambiguously interglacial climate conditions with the occurrence of *Abies* and *Tsuga* in large parts of the spectra. The stable isotope composition of ice wedges also reflects warm climatic conditions in the lower part of the profile. Consequently, a very warm phase occurred in Central Alaska, whose timing is uncertain due to conflicting age determinations and proxy indications.

Keywords: Central Alaska; climate reconstruction; ground ice; permafrost dating; Quaternary environment.

Introduction

Permafrost consists of sediment and ground ice preserving suitable signals for the reconstruction of Late Quaternary environment and climate. Thermokarst, thermoerosion, and slumping often prevent the possibility of resampling a permafrost outcrop. Therefore, underground excavations and permafrost tunnels such as the Fox and Vault Creek (VC) tunnels, may serve as three-dimensional natural laboratories for permafrost studies including dating techniques.

Especially in Central Alaska, where the chronology of sediments is still insufficiently known for the interval between 25 and 100 ka BP (Berger 2003), such revisitable sites are valuable for regional environmental reconstruction. Dating of deposits in this region is based upon a variety of methods including thermoluminescence (TL), infrared or optical stimulated luminescence (IRSL, OSL), fission track (FT), and ^{14}C, which led (and may further lead) to a substantial improvement of the knowledge on timing and duration of Late Quaternary warm and cold phases in Central Alaska. Here we present new data from the Central Alaskan Vault Creek permafrost tunnel near Fairbanks.

Study Area

The Fairbanks area is characterized by discontinuous permafrost and a continental climate with mean annual air temperatures of about -3.0ºC and precipitation of 263 mm (at Fairbanks airport, 1971–2000). Presently, spruce-birch-aspen taiga dominates the vegetation. Permafrost may reach a thickness of up to 120 m and is relatively warm with ground temperatures about -0.8°C at 2 m below ground surface at the tunnel site. The active layer reaches about 0.3 to 0.4 m.

Figure. 1. Study site: The Vault Creek tunnel north of Fairbanks. Additionally, an open pit near Fox was sampled.

Permafrost usually dominates valley bottoms and north slopes, but is largely absent on south-facing slopes. The VC tunnel is situated on a north-facing slope. Frost cracking activity is presently reduced in Interior Alaska. In Wisconsin times, when mean air temperatures were 4°C lower, ice wedge formation was a more common process. In the

Fairbanks region, permafrost is generally considered to have thawed and reset after Sangamon interglacial (Pewe 1975).

The VC tunnel is situated about 40 km north of Fairbanks, Alaska. It was established in 1990 by a local private gold miner and is, to our knowledge, the deepest (>40 m) and longest permafrost tunnel (>200 m) for periglacial research. The entrance of the VC tunnel is secured by a 30 m long steel tube, which makes the uppermost part of the section inaccessible (Fig. 1). This part has been sampled in a 3.0-m-deep auger hole (26 inches or 0.65 m in diameter) located about 50 m ENE of the tunnel's entrance (Fig. 2).

Results

The methodological approach applied to the permafrost sequence of the VC tunnel includes different dating techniques, sedimentology, and palynology, as well as stable isotope geochemistry ($\delta^{18}O$ and δD) of ground ice.

Sedimentology

The sedimentary and geocryological sequence is similar to that of the Fox research tunnel constructed in 1963 by the US Army Corps of Engineers (CRREL). About 40 m of Quaternary deposits overlie weathered schistose bedrock ("Birch-Creek schist"). The Quaternary deposits are: **(1)** at the bottom, 17.5 m of fossiliferous ice-bonded fluvial gravels with several sand and peat lenses, as well as numerous wood remains (depth: 22.5–40.05 m). No ice wedges occur in the gravel horizon; **(2)** in the upper part, about 12 to 15 m of ice-rich silty sediments are found (depth: 3–15 m). These are loess-like, organic-rich, and contain fossil bones, as well as relatively large ice wedges. The silt horizon has a very uniform unimodal grain size distribution (mean 52 µm). Between these two units: **(3)** a 7.5 m thick transition horizon of fluvial gravels interbedding with loess-like silt and relatively small ice wedges was distinguished (depth: 15–22.5 m).

The general sequence is characterized by mean total organic carbon (TOC) content of about 3%. Two horizons of higher TOC content (of up to 18%) are found at about 7.5 m and 23.5 m depth, respectively. C/N ratios are around 8, but significantly higher (reaching 20) at the TOC-enriched horizons. Carbonate contents (Cc) are, in general, below 1.5% (mean Cc 1.1%), but reach a maximum of up to 4.3% at 22.5 m depth. The mass-specific magnetic susceptibility (MS) is low in the transition and gravel horizons (mean MS: 24 and 30.10^8 SI, respectively), whereas the silt displays higher mean MS of almost 70.10^8 SI. The ice contents are significantly higher in the silt (up to 60 wt%) as compared to the gravels (max. 20 wt%). Both ground ice and sediments were significantly deformed by post-depositional slope processes, especially in the upper part of the sequence.

Two 1 to 3 mm thick layers of tephra were detected in the tunnel at about 2 m depth and at about 15.4 m depth. These white ash layers are yet unidentified. Especially the upper tephra is disturbed by creeping or sliding of slope material. At 15.7 m, three up to 20 cm thick ice bands intersect with sediments and ice wedges. Contacts between ice wedges and ice bands are similar to features interpreted as thermokarst-cave ice in the Fox tunnel (Shur et al. 2004) following melt and erosion of a part of an ice wedge by running water. No frost cracking occurred after refreezing of meltwater, so ice wedges were or became inactive after the melt event.

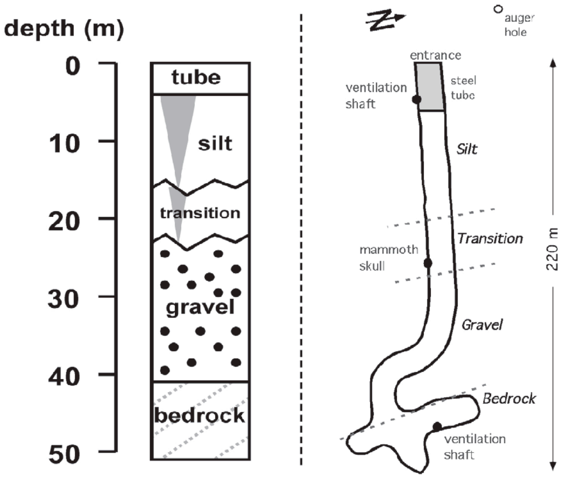

Figure 2. Schematic sedimentary profile of the VC tunnel and top view of the VC tunnel (schematic).

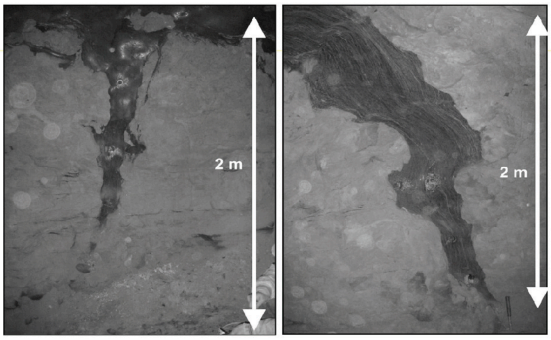

Figure. 3. Ice wedges of the VC tunnel of the silt horizon (left) and transition horizon (right). Note: deformation structures.

Geocryology

The different types of ground ice in the VC tunnel include massive ice such as: **(1)** ice wedges, the most important type of ground ice in the VC tunnel. These are associated only with the silt and transition horizons (Fig. 3).

They are wider (up to 3 m) and more strongly deformed in the upper section than in the transition horizon, where only small, vertically oriented ice wedges of 0.1-0.4 m in width were observed. Ice wedges in the silt horizon show signs of syngenetic growth. The inclination of ice wedges is stronger at the topmost part of the profile reaching up to 45–50° from the vertical line. This indicates a post-depositional transport of material e.g., by slumping or, more likely, by creeping without melting the wedge ice, which reacted plastically. Tops of ice wedges are visible in several cases, especially in the transition horizon; (2) thermokarst cave ice as also recognized in the Fox tunnel (Shur et al. 2004); and (3) a strange type of clear ice is observed at the wall with huge

Table. 1. Summary of all Radiocarbon and IRSL dated sediment and ice wedge samples of the VC tunnel, Fairbanks, Alaska

Sample ID	Depth (m)	Radiocarbon age (a BP)	Type of organic, Stratigraphic position	Lab number
FAI 4/7	0.75	2505 +/-25	wood remains in soil horizon (auger hole)	KIA 31128
FAI 4/5	1.35	3445 +/-35	soil horizon (auger hole)	KIA 31127
FAI 3/20	2.7	25,320 +/- 240	peat inclusion, topmost sample in VC tunnel (silt unit)	KIA 31125
FAI-1/42	2.8	45,120 +3300/-2330	grass roots (silt unit)	KIA 25271
FAI-1/40	4.6	44,220 +1700/ - 1400	wood, organic remains (silt unit)	KIA 28133
FAI-IW-4	5.0	46,120 +4080/ -2690	organic matter in wedge ice (silt unit)	KIA 25660
FAI-1/39	6.4	43,670 + 1480/ -1250	plant remains, leached residue (silt unit)	KIA 28132
FAI-IW-8	7.5	>40,970	organic matter in wedge ice (silt unit)	KIA 25661
FAI-1/37	8.4	49,930 + 3800/ -2570	wood, organic remains Z(silt unit)	KIA 28131
FAI-1/36	9.3	52,390 +2210/ - 1730	wood, organic remains (silt unit)	KIA 28130
FAI-1/34	10.9	42,090 +3410/-2380	silt. organic-rich.	KIA 24873
FAI-IW-12	12.0	34,400 +4390/-2820	organic matter in wedge ice (silt unit)	KIA 25275
FAI-1/30	13.3	> 52,440	wood, organic remains (silt unit)	KIA 28128
FAI-1/33	14.7	42,170 +3480/-2420	organic remains (silt unit)	KIA 28129
FAI mammoth	16.7	> 50,920	small fragments of mammoth skull, collagen, (transition horizon)	KIA 31124
FAI-1/26	19.6	49,550 +2190/-1720	wood remains (transition horizon)	KIA 25270
FAI-1/19	21.7	> 51,130	peat lens (transition horizon)	KIA 24872
FAI-1/2	34.8	> 52790	wood remains (gravel horizon)	KIA 24871
FAI-IW-18	open pit	3615 +/- 45	peat in wedge ice	KIA 25276
FAI-2-1	open pit	4625 +/- 50	small twig	KIA 25272
Infrared-stimulated optical luminescence (IRSL)				
FAI-OSL-2	20.4	75,000+/-10,000	middle sand (transition horizon)	
FAI-OSL-1	21.0	57,000 +/-4400	middle sand (transition horizon)	

crystals of several cm in diameter, most likely related to mining activity. These locations were avoided while sampling in the tunnel. Intrasedimental ice includes segregated ice, as thin layers of ice often bound upward near ice wedges, and finely dispersed pore ice, as well as ice lenses.

Dating

To assess the stratigraphic position of the VC tunnel, several dating techniques were applied (AMS ^{14}C, IRSL, U/Th). The results are summarized in Table 1 and Figure 4. Radiocarbon analyses were carried our at Leibniz laboratory in Kiel, IRSL dating at the Technical University of Freiberg and U/Th dating at GGA Institute in Hannover, Germany. A first stratigraphic scheme is mainly based upon ^{14}C dates.

Samples taken from the auger borehole show a Late Holocene sediment accumulation and soil development around 2.5 to 3.5 ka ^{14}C BP. These dates are similar to those of an open pit near Fox, where peat and ice wedges grew in the second half of the Holocene. The uppermost sample in the VC tunnel (silt horizon) was dated to 25.3±0.2 ^{14}C ka BP. Seven finite ^{14}C dates were measured in the sediments of the silt unit, all between 40,000 and 50,000 ^{14}C BP with a relatively large error bar. Two radiocarbon ages in the silt horizon are beyond dating range. One ice wedge of the silt unit was dated to 34,400+4,390/-2,820 ^{14}C BP. Ice wedges are vertical features, thus, younger organic remains might reach deeper parts of the profile, if the ice wedge was active after sediment accumulation.

From the transition and gravel horizons, three infinite ^{14}C ages of older than 50 ka BP were retrieved, among them one age from a mammoth skull. Only one finite age of 49,550 +2,190/-1,720 ^{14}C BP was measured in the transition horizon. Two IRSL ages in the transition horizon of 57±4.4 ka and 75±10 ka were measured between 20 and 21 m depth confirm the hypothesis of a Wisconsin age of transition and silt horizons. The fluvial gravel might be even older. The attempt to date peat material from the gravel unit by means of U/Th failed due to open system conditions and the subsequent loss of uranium and only an unreliable age (of 360–460 ka) was obtained.

Palynology

Pollen spectra from the VC tunnel can be subdivided into 5 main pollen zones (PZ-I to PZ-V). Oldest pollen spectra (PZ-I, below 27 m) reflect that spruce-birch forest with dwarf birch and shrub alder dominated at the site during that time. The climate was wet and warm, and the studied pollen spectra are unambiguously pointing to “interglacial environmental conditions” similar to Holocene ones.

Pollen spectra of PZ-II (17.5-27 m) are composed of Cyperaceae, *Picea*, *Betula*, Ericales and *Sphagnum* spores showing that spruce forest with some birch trees dominated

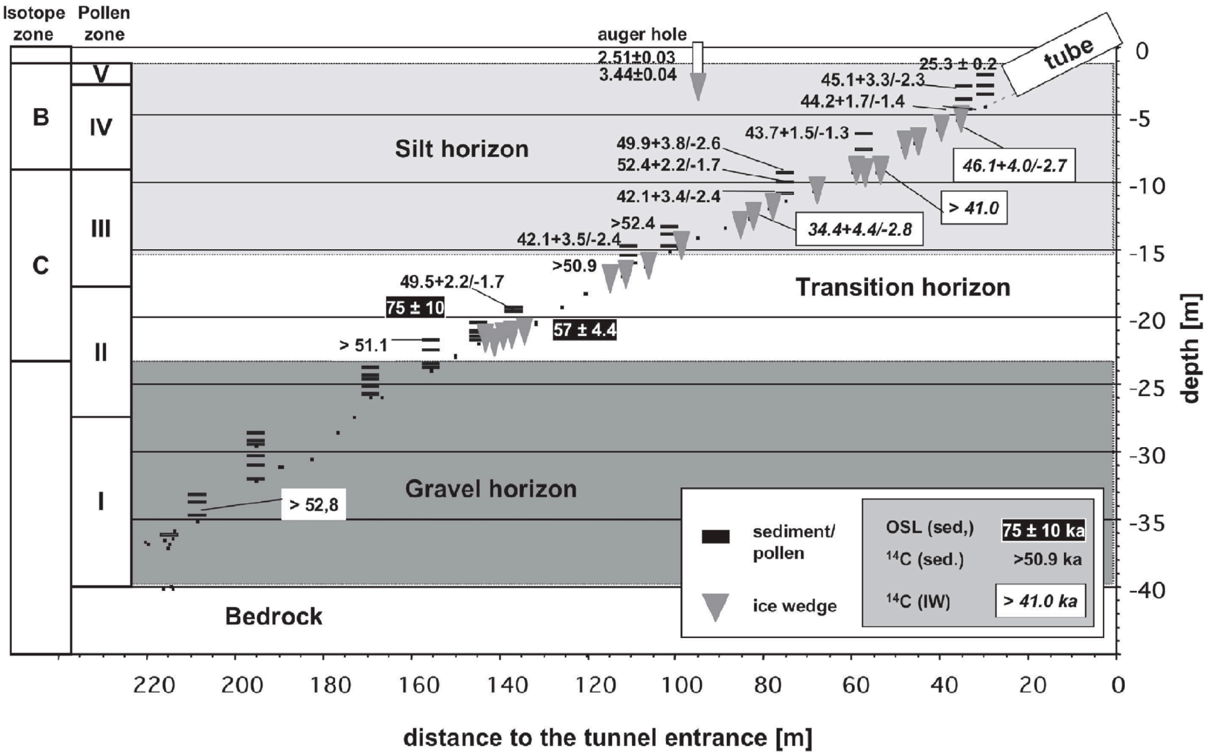

Figure. 4. Stratigraphic position of all sampled sediment profiles and ice wedges as well as their respective sedimentary horizon, pollen zone and isotope zone. Results of all IRSL and radiocarbon AMS ^{14}C dated samples are positioned at their right depth.

at the site during that interval. The find of relatively heavy pollen not readily transported by wind, such as hemlock (*Tsuga*) and fir (*Abies*) may reflect their presence in the local vegetation. The pollen spectra of PZ-III (8–17.5 m) are dominated by *Picea* and Cyperaceae pollen reflecting that spruce forest still dominated at the site. The permanent presence of hemlock and fir in the spectra reflects, most likely, that these trees grew around or not far from the site. Nowadays, these taxa occur in Alaska only in the rather moist coastal areas, where annual precipitation reaches at least 600 mm and winter and summer temperatures range from -6°C to -2°C and 13°C to 16°C, respectively (Viereck & Little 1972). Thus, during the PZ-III interval, climate conditions were probably wetter and warmer than today, e.g., such as in a warm stage of an interglacial. It should be stressed that redeposition seems unlikely due to the good preservation of pollen grain, even though both taxa are known from Tertiary deposits in Alaska (Ager et al. 1994).

A decrease of *Picea* and an increase of Cyperaceae pollen content in the pollen spectra of PZ-IV (depth: 2.8–8 m) may reflect a slight deterioration of the environmental conditions. However, spruce forest still dominated in the local vegetation. The presence of few hemlock and fir pollen shows, however, that climate conditions were still wet and warm during the PZ-IV interval. In pollen zones PZ-I to PZ-IV, typical cold indicators are missing.

Pollen zone PZ-V includes two samples from the uppermost part of the VC tunnel (2.0–2.7 m, near the entrance) reflecting a treeless environment and a significant deterioration of the climate conditions, which were extremely dry and cold during this time. A radiocarbon age of 25,320±240 a BP reflects a Late Wisconsin age of PZ-V.

Stable isotope geochemistry

Ice wedges are periglacial features giving information about winter temperatures which may be derived by stable oxygen and hydrogen isotopes (e.g,, Vaikmäe, 1989, Vasil'chuk 1992, Meyer et al. 2002). Ice wedges are fed by snowmelt or snow directly entering frost cracks, and thus are directly linked with atmospheric moisture. The isotopic composition of single ice wedges and other types of ground ice has been measured with a Finnigan Delta-*S* mass spectrometer using equilibration technique with a precision of ±0.1‰ for δ^{18}O and ±0.8‰ for δD. Significant differences have been observed in the isotopic composition of single ice wedges as well as in the other types of ground ice. Ice wedges have been subdivided into main isotope zones (A), (B), and (C).

The ice wedge of an open pit near Fox (A), directly dated to 3.6 ka ^{14}C BP, shows a mean δ^{18}O and δD of -21.8‰ and -172‰, respectively. This is a typical isotopic signature for ice wedges of Holocene age and may therefore be used as equivalent for interpretation of ice wedges in the VC tunnel.

The stable isotope composition of ice wedges in the tunnel displays two zones of varying winter temperatures: (B) 2.8–8 m depth. Ice wedges are characterized by lowest respective mean δ^{18}O and δD of about -26.5‰ and -210‰, thus, by relatively coldest winters. This estimate is based upon 8 single ice wedges with mean oxygen isotopic composition between

-29.3‰ (at 2.8 m, auger hole) and -23.6‰ (at 6.3 m). This indicates a certain degree of variability of winter climatic conditions, but nonetheless glacial conditions especially in the uppermost part, where lightest (most negative) isotopic composition is reached.

(C) 8–22 m depth. A much higher mean $\delta^{18}O$ and δD of about -22‰ and -175‰, respectively, is observed in the 14 ice wedges of isotope zone C. Mean oxygen isotopic composition in single ice wedges varies from -24.2‰ (at 10.2 m) and -20.5‰ (at 21 m). This could reflect winter temperatures similar to the present ones or, in parts, even warmer as today. Especially in the transition horizon, relatively heavy isotopic composition in ice wedges between -20‰ and -21‰ are common. This relatively clear subdivision is possible despite the fact that ice wedges, predominantly vertical features, propagate downward into older sediments. Between 13.5 and 15 m depth, ice wedges might have a limited climatic relevance. In this depth range, low d excess (below -2‰) points to secondary fractionation. This might be caused by evaporation/sublimation of snow or the participation of reprecipitated water. Therefore, the relatively variable isotopic composition of ice wedge in this depth range is considered with caution.

The mean isotopic composition of thermokarst-cave ice is $\delta^{18}O$ = -22.1‰, and is thus similar to that of ice wedges in isotope zone C. This points to an event of local melt of ground ice, which was subsequently refrozen as thermokarst-cave ice. Intrasedimental ice (both pore and segregated ice) displays highly variable isotopic composition all over the permafrost sequence due to the fact that this type of ice includes not only winter precipitation. Consequently, the isotopic composition of intrasedimental ice is heavier ($\delta^{18}O$ = -19.8‰, N = 23), with lightest values observed at the top of the silt horizon and heaviest values at the bottom.

Discussion

The environmental history reconstructed from sediments and ground ice of the Vault Creek tunnel revealed a series of new results for Central Alaska. The youngest part of the regional history was derived from samples of an auger hole (as well as of an open pit near Fox) and dated to the 2nd half of the Holocene, where peat accumulation took place, ice wedge growth was common and the climate was relatively wet and warm according to palynology and isotope geochemistry of ice wedges. Obviously, the top of the VC tunnel reveals a part of the environmental history around 25 ka ^{14}C BP. Pollen indicate a cold and glacial climate and treeless vegetation. Lightest isotopic composition in ice wedges (and in intrasedimental ice), also point to coldest climatic conditions for the whole sequence. This section was dated to an interval just some thousand years before Late Glacial Maximum. It also states clearly that at VC tunnel, loess accumulation continued at least until 25 ka BP. At the Fox tunnel, a hiatus was observed between about 14–30 ka BP (Hamilton et al., 1988).

The organic remains in fluvial gravels at the bottom of the sequence show infinite ^{14}C ages, which is also supported by the IRSL dates in the transition horizon. Consequently, fluvial activity must have been strong in Early Wisconsin or even before. At this time, summers must have been warm and wet, leading to the intensification of fluvial activity in the area.

Conflicting dates and proxy indications are especially related to the silt unit, which was AMS ^{14}C dated between 40 and 50 ka BP. Unfortunately, these dates are not always in the right order with increasing ages with depth and display relatively large error bars. Hence, it raises the question how the ages around 40 - 50 ka BP correlate with the extremely warm temperatures derived from pollen analyses (especially PZ-II and PZ -III).

This interval has not been known as very warm until now, whereas around 30 to 40 ka BP, interstadial conditions have been described for various sites. For instance, thaw unconformities in the Fox tunnel (the so called "Fox thermal event") have been dated to 30 to 35 ka BP (Hamilton et al., 1988). In northwest Canada, a mid-Wisconsin Boutellier non-glacial interval with temperatures similar to the present ones has been dated to between 30 and 38 ka BP (Schweger and Janssens, 1980). Three ^{14}C dates from ice wedges fall into this time interval (two from Fox, one from VC tunnel), confirming that in the region, frost cracking was active at that time. For about the same interval, temperatures similar to the present ones have been derived by pollen analysis for a sediment record of the Isabella basin, near Fox (Matthews et al. 1974). In Matthews' study, pollen zone Ab indicates climatic conditions as warm as today around 32 ka BP.

There are only few examples for Alaskan climate records extending beyond this interstadial phase. For instance, pollen spectra at Imuruk Lake, Seward Peninsula were interpreted differently by various authors. Pollen zone i was dated to >37 ka and >34.4 ^{14}C BP and attributed to the Sangamon by Colinvaux (1967). However, Shackleton (1982) assumed a Mid Wisconsin interstadial for this pollen zone. This re-estimate is based, among other methods, upon the assumption that the Old Crow (OC) tephra (predating pollen zone i) is about 80 ka old. New data yield an age for the OC tephra of about 142.3±6.6 ka BP (Berger 2003). Therefore, the pollen spectra at Imuruk Lake must be reinterpreted and at the moment, pollen zone i is more likely interglacial (Sangamon) than interstadial.

Nonetheless, in no other palynological study in Interior Alaska have such warm climatic conditions as in the VC tunnel been derived by means of pollen analyses (Ager & Brubaker, 1985). This is not only valid for a small part of the VC tunnel, but for almost the complete periglacial sequence. This reflects the difficulty of interpreting environmental data beyond radiocarbon dating range and the need to understand more about the environmental history in Alaska. This makes the VC tunnel exceptionally valuable for a more detailed study of this time interval.

To summarize, there are three possibe interpretations of our data: (1) trust the radiocarbon ages. In favor of this hypothesis is the high number of similar and finite ages of the silt horizon, as well as two IRSL ages from the transition horizon predating the loess. This points to a Wisconsin age of both transition and silt horizons. Additionally, the AMS method applied at Leibniz laboratory in Kiel, expanded the dating range back to about 50–70 ka BP (Nadeau et al. 1997, 1998). This assumption would lead to a very warm and as yet unknown interval in mid-Wisconsin times.

The fact that trees grew close to the site allows a second (hypothetical) interpretation, that (2) a small forest existed in the Vault Creek area due to locally different climate conditions (e.g., close to a hot spring) and survived through Wisconsin times. Finally, we can (3) disbelieve the ages, which are near the dating limit, and assign the whole sequence to the Sangamon (or other) interglacial based on interpretation of pollen spectra. A warm phase is supported by relatively heavy isotope composition of the ice wedges. Acceptance of this hypothesis would contradict Pewe's ideas of no ground ice surviving the Sangamon interglacial in Interior Alaska. In any case, winter temperatures must have been cold enough for frost cracking, and summers not so warm as to melt ground ice. This paradox of extremely warm summer temperatures at a presently discontinuous and relatively warm permafrost site, with predominantly loess accumulation in which ground ice was formed and survived, cannot be solved completely. It is likely that sediment transport downslope, redeposition, and burial of ground ice played a key role for the pre-existence of permafrost. At least once, melting influenced the sequence when thermokarst-cave ice was formed after lateral melting of ground ice. This displays the vulnerability of these deposits, but also the possibility of contaminating older deposits by younger organic material.

Conclusions

The late Quaternary record of the Vault Creek permafrost tunnel near Fairbanks spans more than 75 ka and indicates varying environmental conditions from rather fluvial (gravelly) to aeolian (silty) environmental conditions.

Fluvial activity was intensive in the Vault Creek area in or before Early Wisconsin, leading to the deposition of 17.5 m of fluvial gravels. Climate conditions were warm and wet during that time. There are no signs of frost cracking activity at that time.

AMS ^{14}C dates point out that silt accumulation and ice wedge growth took place in the vicinities of the VC tunnel from 40 to 50 ka BP to at least 25 ka BP. A very warm phase with spruce forest environment occurred in Central Alaska, whose timing and duration is still uncertain due to conflicting age determinations and proxy indications. However, a climate deterioration is evident at the top of the section (around 25 ka BP), when the climate was colder than today and a treeless tundra environment prevailed as indicated by pollen and ice wedge isotope geochemistry. During the second half of the Holocene, peat accumulation and ice wedge growth took place.

Acknowledgments

We thank Mr. Sam Skidmore for the field support and valuable suggestions. We also thank Melanie Sierralta from the GGA Institute in Hannover for U/Th dating and Matthias Krbetschek from Freiberg Technical University for providing two IRSL dates.

References

Ager, T.A. & Brubaker, L.. 1985. Quaternary palynology and vegetational history of Alaska. In: V.M Bryant. & R.G. Holloway (eds.), *Pollen records of Late Quaternary North American Sediments*. 353-384.

Ager, T.A., Matthews, J.V. & Yeend, W. 1994. Pliocene terrace gravels of the ancestral Yukon River near Circle, Alaska: Palynology, paleobotany, paleoenvironmental reconstruction and regional correlation. *Quaternary International* 22/23: 185-206.

Berger, G.W. 2003. Luminescence chronology of late Pleistocene loess-paleosol and tephra sequences near Fairbanks, Alaska. *Quaternary Research* 60: 70-83.

Hamilton, T.D., Craig, J.L. & Sellmann, P.V. 1988. The Fox permafrost tunnel: a late Quaternary geologic record in central Alaska. *Geological Society of America Bull.* 100: 948-969.

Matthews, J.V., Jr. 1974. Wisconsin Environment of Interior Alaska: Pollen and Macrofossil Analysis of a 27 Meter Core from the Isabella Basin (Fairbanks, Alaska). *Canadian Journal of Earth Sciences* 11(6): 828-841.

Meyer, H., Dereviagin, A.Yu., Siegert, C., Schirrmeister, L. & Hubberten, H.W. 2002. Paleoclimate reconstruction on Big Lyakhovsky Island, North Siberia – Hydrogen and oxygen isotopes in ice wedges. *Permafrost and Periglacial Processes* 13: 91-105.

Nadeau, M.J., Schleicher, M., Grootes, P.M., Erlenkeuser, H., Gottdang, A., Mous, D.J.W., Sarnthein, J.M. & Willkomm, H. 1997. The Leibniz-Labor facility at the Christian-Albrecht-University, Kiel, Germany. *Nuclear Instruments and Methods in Physics Research* 123: 22-30.

Nadeau, M.J., Grootes, P.M., Schleicher, M., Hasselberg, P., Rieck, A. & Bitterling, M. 1998. Sample throughput and data quality at the Leibniz-Labor AMS facility. *Radiocarbon* 40: 239-245.

Péwé, T.L. 1975. Quaternary Geology of Alaska. *US Geological Survey Prof. Paper* 835: 145pp.

Sellmann, P.V. 1967. Geology of the USA. CRREL permafrost tunnel, Fairbanks, Alaska. Technical Report 199, US Army CRREL. Hanover, New Hampshire, 22 pp.

Schweger, C.E. and Janssens, J.A. 1980. Paleoecology of the Boutellier non-glacial interval, St. Elias mountains, Yukon territory, Canada. *Arctic and Alpine Research* 12. 309-317.

Shur, Y., French, H.M.,Bray, M.T. & Anderson D.A. 2004. Syngenetic Permafrost Growth: Cryostratigraphic Observations from the CRREL Tunnel near Fairbanks, Alaska. *Permafrost and Periglac. Process.* 15: 339-347.

Vaikmäe, R. 1989. Oxygen isotopes in permafrost and ground ice – A new tool for paleoclimatic investigations. *5th Working Meeting Isotopes in Nature, Proceedings, Leipzig, September 1989:* 543-553.

Vasil´chuk, Yu.K. 1992. Oxygen isotope composition of ground ice—application to paleogeocryological reconstructions, Vol. 1, Moscow, Russia: 420 pp.

Viereck, L.A. & Little Jr., E.L. 1972. Alaska Trees and Shrubs. Agriculture Handbook No. 410, Forest Service US Department of Agriculture. Washington DC, 265 pp.