Dating recent permafrost disturbance and recovery with tritium and post-bomb radiocarbon isotopes

F. Calmels, D.G. Froese & W. R. Clavano
Department of Earth and Atmospheric Sciences – University of Alberta, Edmonton, Alberta, Canada.

ABSTRACT
We test the use of tritium and post-bomb ^{14}C from organic samples within permafrost aggradational ice to determine the timing of historic permafrost aggradation. Three of four samples lacked tritium, while testing positive for the presence of excess ^{14}C (F14C). Calibration of these ages using CALIBomb, allows precise ages through comparison with post-bomb atmospheric ^{14}C concentrations. The mostly like age for three of four samples ranged from March 1956-May 1957 (2 sigma) and Sept 1955-Jan 1957 (2 sigma). A fourth sample did not include post-bomb ^{14}C.

RÉSUMÉ
Nous testons l'usage du tritium et du radiocarbone post-bombe sur des matériaux organiques au sein de glace d'aggradation pour determiner la chronologie de épisodes historiques d'aggradation du pergélisol. Trois échantillon sur quatre étaient dépourvus de tritium, tandis qu'ils contenaient un excédant de radiocarbone moderne (F14C). La calibration de ces âges avec CALIBomb, permet de préciser les âges en les comparant aux concentrations de radiocarbone atmosphérique post-bombe. L'âge le plus probable de trois des quatre échantillons s'échelonne de mars 1956 à mai 1957 (2 sigma), et septembre 1955 à janvier 1957 (2 sigma). Un quatrième échantillon ne contenait pas de radiocarbone moderne.

1 INTRODUCTION

Tritium (3H) in pore ice has provided an exceptional tool to understand recent permafrost dynamics, and especially to date whether ground ice was formed subsequent to, or has incorporated, water following the advent of the early 1950s above-ground nuclear testing (Michel and Fritz 1978, 1982, Chizhov et al. 1983, 1985, Dever et al. 1984, Burn and Michel 1988, Burn 1990).

A similar approach can be used with other post-bomb radio-isotopes. Radiocarbon (^{14}C) is naturally produced in the upper atmosphere, and its activity is maintained in a steady state by decay and burial. However, large amounts of radiocarbon were produced during nuclear tests by the resulting high neutron fluxes, and the radiocarbon atmospheric concentration doubled by 1964. This modern carbon (mC) has now almost completely disappeared from the atmosphere, but still can be found in organic materials and oceans. In theory, modern carbon could provide a reliable tool to date permafrost disturbance by dating organic material within aggradational ice, which, to our knowledge, has never been used.

This note presents how tritium and modern post-bomb radiocarbon techniques were used to date two ages of permafrost disturbance and recovery in response to surface vegetation cover disturbances induced by historic mining related activities.

2 STUDY SITE AND HISTORICAL CONTEXT

Permafrost cores were recovered from an area of historical disturbances in the southern Klondike Placer District (goldfields) (Figure 1). An area of a few hundred square meters contains several sites with differing ages of disturbance which allows some assessment of the recovery of permafrost over time. The original surface is a gently sloping (4-5 degrees) pediment developed on loessal silts along the north side of the Dominion Creek valley. Further upslope, the surface grades into a colluvial mantle along the valley margin.

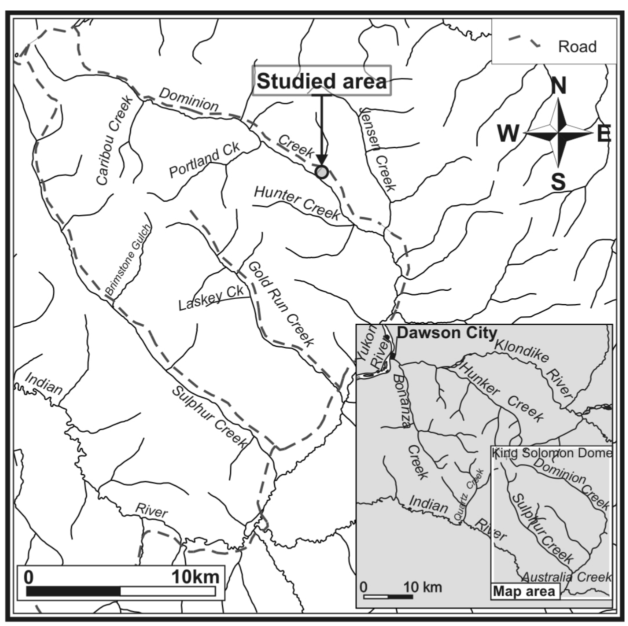


Figure 1. Location of study sites.

The Dominion Creek valley, as in much of the Klondike area, was subject to several periods of disturbance from mining activities dating back to the late 19th century (Green 1977; Morse, 2003). The Goldrush era (beginning ca. 1896) induced heavy deforestation of valleys due to the growing needs of wood for fuel and construction in support of mining. Stumps from mature trees within the forest, as well as evidence of hand-mining (shafts, tools and tailings piles) indicate early mining adjacent to the study site (A. Sailer, pers. comm. 2007). The impact of this deforestation was still visible in the late 1940s, as shown by the 1949 air photo of the study area (Figure 2). By the 1950s, vegetation was recovering but was mostly limited to shrubs, with trees being scarce. Additional disturbances were created to accommodate infrastructure such as roads, railways, telegraph lines, and ditches (Hogan and Skuce, 1992a, 1992b, 1993). Many of these sites were abandoned shortly after construction, but some persisted through the following half-century until large scale mining ended in the 1960s (Green, 1977).

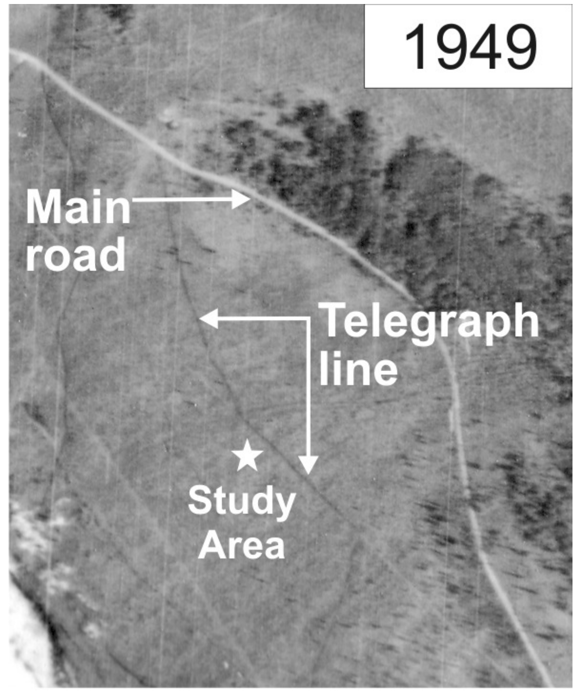
Since the 1960s mechanized mining produced several local disturbances of the surface vegetation cover. In 1992, an adjacent area one hundred meters downslope of study site was stripped of vegetation to induce permafrost thaw in anticipation of future mining (A. Sailer, pers. comm. 2007, Figure 2).

Some roads going through the recovering forest are still present, marked by tracks where trees have been cut, uprooted or scarred, and the peat cover has either been compacted or removed (Figure 3). Two of these, Roads 2 and 3, are too small to be visible on the air photos (Figure 2), but tree ring counts allow estimation of their age. The oldest trees in the study area date to ca. 1930. Living trees along Roads 2 and 3 include prominent tree scars indicating a disturbance in 1992 (16 years prior to 2008), consistent with local information from the miner (A. Sailer, pers. Comm. 2007).

These results suggest: (i) that forest regeneration took place during the late 1950s-1960s, coinciding with the end of heavy mining operations (dredging) in the area, and (ii) that the living trees sampled on the road, with prominent and consistent tree scars, survived the road crossing and are not a new generation of trees following the disturbance. Consequently, Roads 2 and 3 were cleared during the 1992 mining season.

3 SUMMARY OF THE CRYOSTRATIGRAPHIC INVESTIGATION

The results of the cryostratigraphic study are presented and discussed in Calmels and Froese (2009), and Calmels et al. (submitted). Five permafrost cores were recovered in the wooded, mainly undisturbed area, from early June to mid-July 2008 using a light, portable drill, similar to Calmels et al. (2005). The five boreholes (W1, RD[2]1, RD[2]2, RD[3]1, RD[3]2) were drilled in the wood (borehole W1), and in the bulldozer tracks “Road 2” and “Road 3”. Core sections were recovered, wrapped in plastic, and stored in a freezer and returned to the University of Alberta, where they were untouched prior to CT scan imaging. Subsampling of the cores followed the cryostratigraphic observations from CT scanning following the methods established by Calmels and Allard (2004, 2008), and Calmels et al. (2008). The observations allowed the distinction to be made between ice-rich and ice-poor levels, and selection of samples for sedimentary and isotopic analyses with respect to ice content.



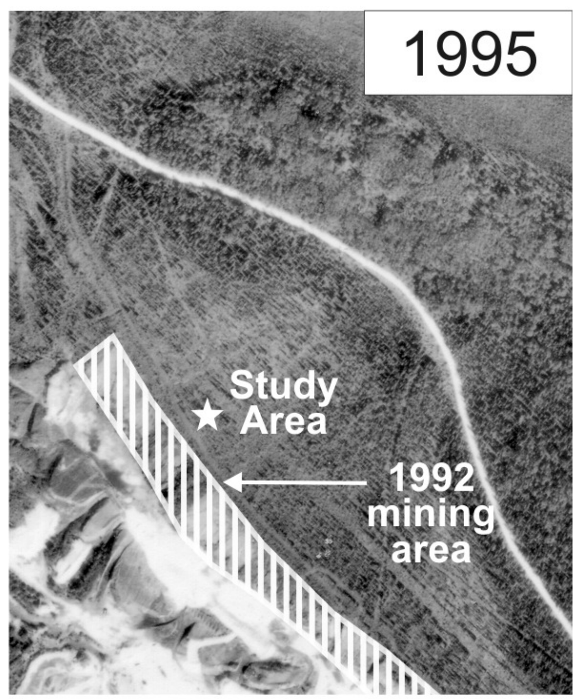


Figure 2. Aerial photographs of the study area from 1949 to 1995.

Figure 3. Vehicle tracks in recovering forest.

Cryostratigraphic observations focused on the permafrost table and ice-rich levels, as the most significant geocryological features observed with respect to the site history. A suspended cryostructure at the boundary between the permafrost table and its active layer indicates a relatively stable permafrost table in the wooded area (W1). The cryostructure of the road sites (RD) indicate that the ice is re-aggrading with subvertical ice lensing extending into the former active layer from the permafrost.

All the cores sampled in the former roads (RD[2]1, 2 and RD[3]1, 2) include two prominent levels of a suspended cryostructure at ca. 100-160 and 150-240 cm depth, while the forested site has only one level at ca. 190-220 cm. Figure 4 summarizes the geocryological setting encountered on the study site. The suspended cryostructure is often associated with the upper ice–rich permafrost boundary, where aggradational ice is common. It could be an indication of the former top of the permafrost table following a past disturbance and subsequent recovery of the active layer. Because the W1 core is located only a few meters from the RD[3] cores, one can expect the sites to have a similar geomorphic history and similar climatic conditions. This suggests that the principal factors leading to any cryostratigraphic differences would come from any surface disturbance history.

As most of the Klondike area underwent deforestation in the early 20th century associated with the Gold Rush, the lower ice-rich level is assumed to be a geocryological imprint of permafrost aggradation induced by the recovery of the forest following this disturbance. Air photos suggest vegetation recovery took several decades, with the forest recovering in the 1950s. The second, upper ice-rich layers, only occurring in Road 2 and 3 cores, likely reflect the recovery from the 1992 road clearing. The lower ice-rich level is similar to the W1 site, and likely records the early 20th century deforestation that would have affected both sites.

Given this surface history, we test this reconstruction using tritium, and modern ^{14}C analyses respectively on samples of ground ice water collected within the upper and lower ice-rich levels, and organic material sampled between both levels.

4 DATING METHODS

4.1 Tritium determination

Tritium (T or ^{3}H) analyses were completed at the University of Waterloo Environmental Isotope Laboratory (EIL). Tritium is a hydrogen isotope, with a half-life of 12.43 years. It is produced naturally by the impact of cosmogenic neutrons on nitrogen nuclei or cosmic ray spallation. Its production in the upper atmosphere provides a typical content in the order of 4 to 15 TU (tritium units) in precipitation. Since 1952, however, tritium produced by above-ground hydrogen bomb tests has exceeded natural production by 2 to 3 orders of magnitude (Clark and Fritz 1997). Tritium analyses can indicate whether or not modern water (post-1950s) contributed to ice formation.

Frozen sub-samples were placed in sealed containers and allowed to melt. Tritium analyses were completed using liquid scintillation counting (LSC), following Calmels et al. (2008). Using a benchmark from previous studies (e.g. Calmels et al. 2008), we assume that samples would have tritium content between 0.8 and 4 TU, requiring a volume of ~500 ml per sample. The samples were enriched approximately 15 times by electrolysis before counting. Due to the large water volume required, only one sample was analysed from the core in site W1 (undisturbed wood), two samples from RD[2]1 (Road 1), and two samples from RD[3]2 (Road 3).

4.2 Modern ^{14}C analyses

Organic matter, primarily fine rootlets, were sampled for radiocarbon dating from cores above the lower ice-rich level at 182 and 226 cm in core W1, at 206 cm in core RD[3]1, and at 180 cm in core RD[3]2 (Figure 4). The purpose was to determine whether enriched levels of radiocarbon are present, indicating that the plant matter incorporated atmospheric CO_2 following above-ground nuclear testing (post-1950s, Reimer et al., 2004). Organic samples were separated by sieving and cleaned in deionized water. Pre-treatment of samples at the University of Alberta followed standard acid-base-acid procedures, with solutions heated to 70 ºC: 30 minutes in 1M HCl, 60 minutes in 1M NaOH with solution changed until clear; 30 minutes in 1M HCl, and rinses with ultrapure water until neutral. CO_2 production, graphitization and measurement of ^{14}C abundance was completed at the Keck-Carbon Cycle AMS facility (UCIAMS, University of California-Irvine Accelerator Mass Spectrometry). Samples containing excess radiocarbon, indicating post-bomb ages, were calibrated using CaliBomb (Reimer et al. 2004), while the remaining sample was calibrated using Calib 6.0.1 and the IntCal09 calibration curve (Reimer et al. 2009; for more detail about CaliBomb, see Queen's University Belfast's web site at http://intcal.qub.ac.uk/CALIBomb/).

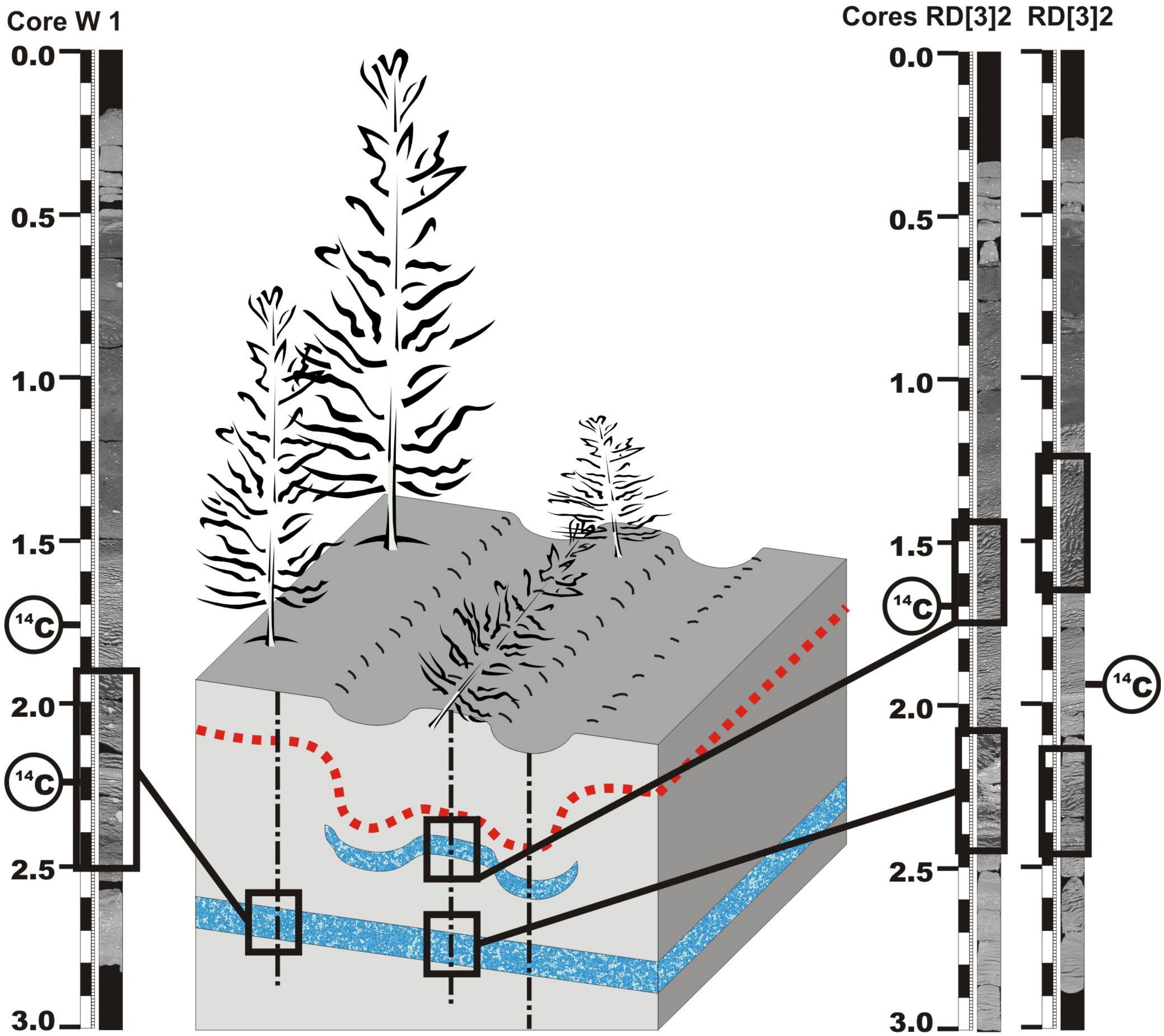


Figure 4. Cryostratigraphical setting in wood and road sites.

5 RESULTS

5.1 Tritium

Tritium determinations were made on melted ice-rich sections of cores where enough water was available for analysis. The wooded area has only a single ice-rich section (W1) which was sampled between 199 and 216 cm. We sampled the ice-rich levels of core RD[2]1 on Road 2 at 124 cm (higher ice-rich level) and a lower section with less ice between 156 and 172 cm (lower ice-rich level). An additional set of samples was taken from the core between the tracks on Road 3 (RD[3]2) at 163 cm (higher ice-rich level) and 235 cm (lower ice-rich level) depth.

All tritium values from the lower ice-rich sections sampled are below 0.8 TU, which suggests sub-modern water (i.e., supplied from water, or recharged prior 1952, Clark and Fritz 1997).

The tritium values from the upper ice-rich sections are 11.9 ± 1 TU for sample RD2[1]-124, and <0.8 ± 0.3 for sample RD3[2]-163. For continental regions, values of 5 to 15 TU are typical for modern water with a time delay of about 5 to 10 years (Clark and Fritz, 1997). In the case of Road 2, the tritium values suggest that the ice of the upper ice-rich section (at ca. 124 cm) was formed during the last decade for road 2, while the tritium value for Road 3 suggests that the ice formed in the 1950s or later, and that the recovery post-dates that time.

5.2 Modern ^{14}C

Three of four radiocarbon dated samples indicate the presence of excess radiocarbon, suggesting a post-bomb age for the samples. Calibration of these ages using

CaliBomb allows correlation to the post-bomb atmospheric radiocarbon concentration (Table 1, Figure 5). The sample W1-226 provides a calibrated range of 1957-1993, providing intercepts in the rising limb of the curve and its declining limb in the 1990s (Figure 5). Samples RD[3]1-206, from 216 to 226 cm depth, and RD[3]2-198H, from 163 to 179 cm depth, have single intercepts at 1955-1957 and 1956-1957. Collectively, these results indicate that permafrost aggraded with the inclusion of organic matter dating to the late 1950s.

6 DISCUSSION

Results show that samples from the deeper aggradational ice lacked tritium, while one sample from the assumed late 20th century level was positive for the presence of tritium. The absence of tritium in the upper ice-rich level in Road 3 could be explained by many differences between Roads 2 and 3. The upper ice-rich level in Road 3 is deeper than in Road 2 and could be older. The Road 3 core includes an organic rich layer in its upper profile. The upper ice-rich level in core RD[3]2 is less clearly defined than that of core RD[3]1, and the organic layer in core RD[3]2 has not been compacted. Any one or a combination of these factors could have influenced the permafrost degradation and/or recovery in a yet unexplained way. The extensive disturbances observed on the early aerial photographs suggest, however, that Road 3 could have existed before, and that the upper ice-rich layer has had a previous period of recovery. The 1992 re-opening of the road may have followed the former path and reset its surface conditions. Post-bomb ^{14}C results of three for four organic samples from two cores showed the presence of excess modern carbon (F14C) in the lower samples, despite the lack of tritium. A fourth sample did not include any post-bomb ^{14}C, giving a calibrated range in the 15th-17th centuries, suggesting older material was likely reworked into the organic sample. The most likely years for two samples ranged from March 1956-May 1957 (2 sigma) and Sept 1955-Jan 1957 (2 sigma) suggesting that the plants ceased metabolizing atmospheric CO_2 in 1956 or 1957, probably when the permafrost table began aggrading as forest succession occurred on the surface. A third sample includes an intercept in the 1957-1958 interval, but also intercepts an early 1990s part of the calibration curve

The results confirm that the ice-rich levels develop mainly at the point where the freezing front is stationary or slowly aggrading, when ice segregation processes generate thicker ice lensing. Such thermal conditions can occur when permafrost degradation stops and the thawing front stagnates. Thereafter, the permafrost table starts to progress upward and regains the active layer. Consequently, these ice-rich levels reflect changes from permafrost degradation to ice re-aggradation.

7 CONCLUSION

To our knowledge this is the first use of post-bomb ^{14}C calibration in permafrost disturbance studies. It is a rapid method that requires very small sample masses, making it particularly well-suited for studies where sufficient pore ice may not be available for the use of tritium. And further, from this pilot study, the technique appears to be more sensitive to recording post-bomb events than simply using the presence or absence of tritium in pore water. This technique may be more broadly applied as a means to document and characterize recent changes in near-surface permafrost, and to provide tangible information about the future evolution of permafrost terrain under a predicted warmer climate.

ACKNOWLEDGEMENTS

We thank the Sailer family who have been mining in the study area for many decades and who have provided us with detailed descriptions of the history of their land, which informed much of the sampling strategy that we used in this study. We particularly appreciate the help of Alberto Reyes and Chris Atkins for field assistance. Funding for this research was provided by a contract from the Yukon Geological Survey, in addition to support from Fonds Québécois de la Recherche sur la Nature et les Technologies to F. Calmels, and from the Natural Sciences and Engineering Research Council of Canada (NSERC) and Alberta Ingenuity New Faculty Award to D. Froese.

Laboraty number	Sample name	Fraction modern (F14C)	D14C (‰)	^{14}C age (BP)	Age range 2 sigma (yr.)	Probable age
UCIAMS-70807	W1-182	0.9619±0.0025	-38±25	310±25	1491-1647	
UCIAMS-70806	W1-226	1.1386±0.0023	138.6±2.3	-1040±20	1957 (Oct.) – 1993 (Oct.) Most probable: 1957 (Oct.) – 1958 (Mar.)	1957
UCIAMS-70808	RD[3]2-198	1.0621±0.0025	62.1±2.5	-480±20		1957
UCIAMS-70809	RD[3]1-206	1.0439±0.0022	43.9±2.2	-340±20		1956

Table 1. Age range from post-bomb ^{14}C dating.

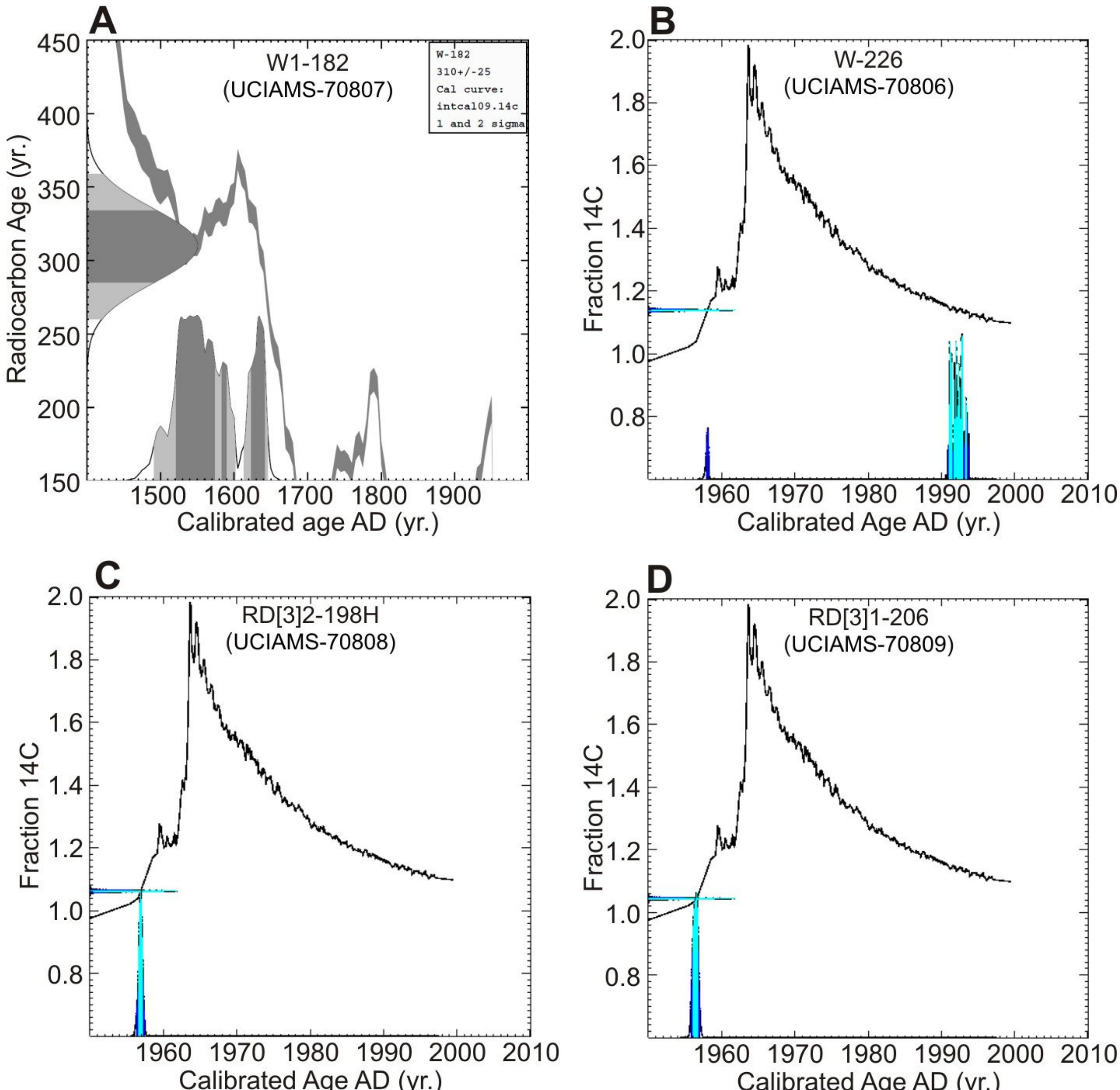


Figure 5. ^{14}C calibrated age curves.

A: Calibrated age of UCIAMS-70807 using Calib 6.0.1 and Intcal09 curve(reimer et al., 2009), the sample w1-182 does not include any post-bomb ^{14}C, giving a calibrated range in the 15th-17th centuries; B,C,D: Calibrated ages of samples # UCIAMS-70806, UCIAMS-70808, UCIAMS-70809 using Calibomb. The sample W1-226 provides a calibrated range of 1957-1993, providing intercepts in the rising limb of the curve and its declining limb in the 1990s. Samples RD[3]1-206 and RD[3]2-198H have single intercepts at 1955-1957 and 1956-1957.

REFERENCES

Burn, C.R. and Michel, F. A. 1988. Evidence for recent temperature-induced water migration into permafrost from the tritium content of ground ice near Mayo, Yukon Territory, Canada. Canadian Journal of Earth Sciences, 25: 909-915.

Burn, C.R. 1990. Implications for palaeoenvironmental reconstruction of recent ice-wedge development at Mayo, Yukon Territory. Permafrost and Periglacial Processes, 1: 3-14.

Calmels, F. and Allard, M. 2004. Ice segregation and gas distribution in permafrost using tomodensitometry analysis. Permafrost and Periglacial Processes, 15: 367-378.

Calmels, F. and Allard, M. 2008. A structural interpretation of the palsa/lithalsa growth mechanism through the use of CT scanning. Earth Surface Processes and Landforms, 33: 209-225.

Calmels, F. and Froese, D.G. 2009. Cryostratigraphic record of permafrost degradation and recovery following historic surface disturbances, Klondike area, Yukon. Yukon Exploration and Geology 2008: 85-97.

Calmels, F., Gagnon, O. and Allard, M. 2005. A portable earth-drill system for permafrost studies. Permafrost and Periglacial Processes, 16: 311-315.

Calmels, F., Delisle G. and Allard, M. 2008. Internal structure and the thermal and hydrological regime of a typical lithalsa: significance for permafrost growth and decay. Canadian Journal of Earth Sciences, 45: pp. 31-43

Chizhov, A.B., Chizhova, N.I., Morkovkina, I.K. and Romanov, V.V. 1983. Tritium in permafrost and ground ice. Proceedings, 4th International Conference on Permafrost, National Academy of Sciences, Washington, DC, USA, 1: 147 - 151.

Chizhov, A.B., Chizhova, N.I., Romanov, V.V., Morkovkina, I.K. and Boyorskoi Y.G. 1985. Tritium analysis in geocryological research. International Geology Review, 27: 1370 - 1377.

Dever, L., Hillaire-Marcel, C. and Fontes, J.C. 1984. Composition isotopique, géochimie et genèse de la glace en lentilles (palsen) dans les tourbières au Nouveau Québec (Canada). Journal of Hydrology, 71: 107- 130.

Clark, I. and Fritz, P. 1997. Enviromental Isotopes in Hydrogeology. Lewis Publishers, New York, USA.

Froese, D.G., Westgate, J.A., Reyes, A.V., Enkin, R.J. and Preece S.J., 2008. Ancient permafrost and a future warmer Arctic. Science, 321: 1648.

Green, L. 1977. The gold hustlers. Alaska Northwest Publishing Company, Anchorage, Alaska. USA.

Hogan, B. and Skuce, G. 1992a. Klondike Mine Railway. Preliminary Survey and Field Recording Project. Dawson City Museum and Historical Society, Yukon, Canada.

Hogan, B., and Skuce, G. 1992b. North Fork Power Project. Preliminary Survey and Field Recording. Dawson City Museum and Historical Society, Yujkon, Canada.

Hogan, B., and Skuce, G. 1993. Yukon Ditch. Klondike Siphon to Bonanza Creek. Preliminary Survey and Field Recording Project. Dawson City Museum and Historical Society, Yukon, Canada.

Lawrence, D.M. and Slater, A.G., 2005. A projection of severe near-surface permafrost degradation during the 21st century. Geophysical Research Letters, vol. 32, L24401.

Michel, F.A. and Fritz, P. 1978. Environmental isotopes in permafrost related waters along the Mackenzie Valleycorridor. In Proceedings of the Third International Conference on Permafrost, Nationa. Research Council of Canada, Ottawa, ON, Canada, 1: 207-211.

Michel, F. A. and Fritz, P. 1982. Significance of isotope variations in permafrost waters at Illisarvik, N.W.T. In Proceedings of the Fourth Canadian Permafrost Conference, Calgary. Alberta (ed. H. M. French). National Research Council of Canada, Ottawa, ON, Canada: 173-181.

Morse, K. T. 2003. The Nature of Gold: An Environmental History of the Klondike Gold Rush. University of Washington Press, Washington, D.C., USA.

Reimer, P.J., Brown, T.A., and Reimer, R.W. 2004. Discussion: Reporting and Calibration of Post-Bomb14C Data. Radiocarbon 46: 1299-1304

Reimer, P. J., Baillie, M.G. L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J. and Weyhenmeyer, C.E. 2009. IntCal09 and Marine09 Rradiocarbon Age Calibration Curves, 0–50,000 Years CAL BP. Radiocrabon, 51: 1111–1150.

Slaymaker, O., and Kelly, R.E.J. 2007. The Cryosphere and Global Environmental Change. Blackwell Publishing, Oxford, UK.