"Reconstruction of Little Ice Age Events in the Canadian Rocky Mountains"

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Géographie physique et Quaternaire, vol. 40, n° 1, 1986, p. 17-28.

Géographie physique et Quaternaire, 1986, vol. XL, n° 1, p. 17-28, 10 fig., 5 tabl.

RECONSTRUCTION OF LITTLE ICE AGE EVENTS IN THE CANADIAN ROCKY MOUNTAINS

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ABSTRACT The well-developed moraines of the 'Little Ice Age' represent the most significant regional Holocene glacial event in the Canadian Rocky Mountains. The application of dating techniques (documentary sources, dendrochronology, lichenometry and radiocarbon dating) appropriate to this timeframe are briefly reviewed and summary data from 33 glaciers are presented. Three main periods of moraine development are recognised (i) 1500-1700 A.D., represented by small fragments of poorly dated moraines, (ii) early 1700's when about one-third of the glaciers show a maximum advance, (iii) mid- to late-nineteenth century when major readvances built moraines close to or beyond (i) and (ii). In addition to these periods, ^{14}C dates from overridden trees indicate a 12th/13th century glacial advance to within 400 and 1400 m of the Little Ice Age Maximum positions at Robson and Kiwa (Premier Range) Glaciers respectively. Prior to this advance a period of warmer conditions is inferred between *ca.* 700-1100 A.D. from the presence of large, ^{14}C-dated snags at tree-line near the Athabasca Glacier, including a 1000 ^{14}C yr-old larch (probably *Larix lyallii*) about 90 km northwest of its present limit. Tree-line may have readvanced at the Athabasca site between *ca.* 1300-1700 A.D. but receded again during the eighteenth and nineteenth centuries. Future research should be directed towards using the relatively long tree-ring records (500-1000 yrs, with cross-dating) of this area for climatic reconstructions.

RÉSUMÉ *Reconstitution des événements survenus dans les Rocheuses du Canada au cours du Petit Âge glaciaire.* Les moraines bien développées mises en place au cours du Petit Âge glaciaire sont les témoins les plus importants des glaciations holocènes dans les Rocheuses. On passe ici en revue les principales techniques de datation (sources de documentation, dendrochronologie, lichénométrie et datations au radiocarbone) appropriées à cette période et on présente les données résumées sur 33 glaciers. On a reconnu trois principales phases de développement des moraines caractérisées par : i) quelques tronçons de moraines imparfaitement datées entre 1500 et 1700 ap. J.-C. ; ii) une avancée maximale au début du XVIII^e^ s. pour environ le tiers des glaciers ; iii) des récurrences majeures survenues de la deuxième moitié à la fin du XIX^e^ s. qui ont rejoint sinon dépassé les positions atteintes en i) et ii). Certaines datations au radiocarbone à partir d'arbres ravagés démontrent qu'une avancée glaciaire aux XII^e^ et XIII^e^ s. s'est approchée, jusqu'à 400 et 1400 m respectivement, des positions atteintes à l'apogée du Petit Âge glaciaire aux glaciers Robson et Kiwa. De grosses souches datées au ^{14}C, situées à la limite des arbres près du glacier d'Athabaska, et notamment un mélèze vieux de 1000 ans (probablement *Larix lyallii*) trouvé à 90 km au nord-ouest de la limite actuelle des arbres, démontrent qu'un épisode plus chaud a prévalu entre 700 et 1100 ap. J.-C. La limite des arbres était probablement non loin de ce site vers 1300-1700 ap. J.-C., mais elle a de nouveau reculé au cours des XVIII^e^ et XIX^e^ s. Les recherches sur les reconstitutions climatiques dans la région devront certainement tenir compte de cette longue série de données (500-1000 ans) sur les anneaux de croissance.

ZUSAMMENFASSUNG *Rekonstruktion der Ereignisse in den kanadischen Rockies während der kleinen Eiszeit.* Die gut entwickelten Moränen der "kleinen Eiszeit" sind das wichtigste regionale Eiszeit-Ereignis in den kanadischen Rocky Mountains während des Holozän. Die Anwendung von zu diesem Zeitrahmen passenden Datierungstechniken (dokumentarische Quellen, Dendrochronologie, Lichenometrie und Radiokarbondatierungen) werden kurz besprochen und zusammengefaßte Daten von 33 Gletschern werden vorgestellt. Drei Hauptperioden der Moränen-Entwicklung werden festgestellt: (i) 1500-1700 v.u.Z., charakterisiert durch kleine Fragmente ungenügend datierter Moränen; (ii) eine Periode des frühen 17. Jahrhunderts, als etwa ein Drittel der Gletscher einen maximalen Vorstoß aufweisen; (iii) mittleres bis spätes 19. Jahrhundert, als Hauptrückvorstöße zur Bildung von Moränen führten, die denjenigen von (i) und (ii) glichen oder darüber hinausgingen. Zusätzlich zu diesen Perioden zeigen ^{14}C Daten von zerstörten Bäumen einen Eisvorstoß im 12./13. Jahrhundert, der sich bis auf 400 bzw. 1400 m den Maximal-Positionen der kleinen Eiszeit am Robson und Kiwa-gletscher näherte. Vor diesem Vorstoß wird auf eine Periode wärmerer Bedingungen geschlossen zwischen etwa 700-1100 v.u.Z., auf Grund des Vorkommens von auf ^{14}C datierten großen Baumstümpfen an der Baumgrenze in der Nahe des Athabasca-Gletschers, einschließlich einer 1000 Jahre alten ^{14}C Lärche (wahrscheinlich *Larix lyallii*), die etwa 90 km nordwestlich ihrer gegenwärtigen Grenze gefungen wurde. Die Baumgrenze ist möglicherweise zwischen 1300-1700 v.u.Z. bis zum Athabasca-Gebiet rückvorgestoßen, dann aber wieder während des 18. und 19. Jahrhunderts zurückgewichen. Zukünftige Forschung über die klimatische Rekonstruktion sollte in diesem Gebiet auf die Nutzung der relativ langen Baumring-Belege gerichtet werden (500-1000 Jahre, mit Quer-Datierung).

The well-developed moraines of the last few centuries (Little Ice Age or Cavell Advance, LUCKMAN and OSBORN, 1979; OSBORN, 1982) are conspicuous throughout the Canadian Rocky Mountains (Fig. 1). These landforms document the most significant regional Holocene glacial event in terms of downvalley extent, ubiquity and probable magnitude. At most localities they are the only direct evidence for glacial advances of post-Hypsithermal (Neoglacial) age. However, apart from the classic work of HEUSSER (1956) there has been relatively little work on Little Ice Age deposits in the Canadian Rockies. This paper will briefly review problems associated with dating techniques appropriate to this time frame in the Rockies, evaluate the available chronology with particular reference to the early history of the Little Ice Age, and make suggestions for further research. The review will focus on work carried out in and adjacent to Jasper National Park over the last 10 years (Fig. 1).

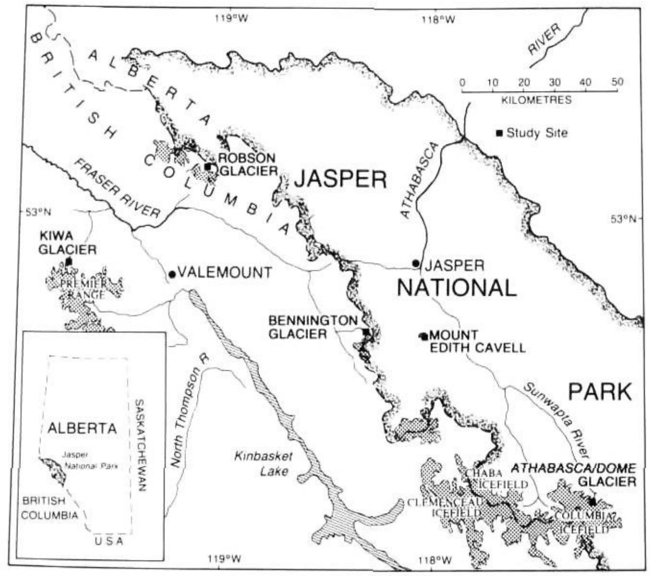

FIGURE 1. Location of major study sites

Localisation des principaux sites étudiés.

DATING TECHNIQUES

Several good general reviews of dating techniques in this timeframe have been published recently, *e.g.* PORTER (1981) and BRADLEY (1985), and this material will not be repeated here. Standard relative-age dating techniques involving morphologic and stratigraphic relationships are clearly applicable but, as yet, no well-dated sections with multiple Holocene tills comparable to those of ROTHLISBERGER (1976), RYDER and THOMSON (1986) or OSBORN (1986) have yet been reported for the Canadian Rockies. At Boundary Glacier near the Columbia Icefield, GARDNER and JONES (1985) have recently provided the first well-dated evidence of a Neoglacial advance older than the Little Ice Age in the Canadian Rockies. This site was ice covered until *ca.* 1970 A.D. but the section only contains a single till unit, 1.5 m thick, overlying wood and peat dated at 3880 ± 60 yr BP (WAT 1183) and 4050 ± 70 yr BP (WAT 1182), respectively.

Although the Little Ice Age moraines are conspicuously large their morphological simplicity may belie a much more complex history. In many cases the earlier Little Ice Age (or pre-Little Ice Age) moraines are fragmentary and/or partially overriden by later moraines, *e.g.* evidence of the early eighteenth century advance of the Athabasca Glacier (see below) is preserved at only two small localities just outside the mid-nineteenth century moraine. Therefore it is quite possible that many of these moraines (particularly laterals) may have been built up during several periods of glacial advance but the surface morphology and age simply reflect the last occupation (see LUCKMAN and OSBORN, 1979; OSBORN, 1986).

DOCUMENTARY SOURCES

Unlike some European localities (*e.g.* ROTHLISBERGER, 1976; ZUMBUHL, 1980) documentary records of former glacier positions in the Canadian Rockies are sparse. The earliest records derive from the influx of tourists and climbers following the completion of the Canadian Pacific Railway to Banff and Lake Louise in the 1880's. Early glacier studies include those by SHERZER (1907) and the fledgling Alpine Club (*e.g.* WHEELER, 1907, 1912) but probably the most useful regional sources are the photographic survey of Jasper National Park by E. M. BRIDGELAND (1915) and the photo-topographic work of the Interprovincial Boundary Commission between 1913 and 1924 (CAUTLEY *et al.*, 1917; CAUTLEY and WHEELER, 1924, 1925). The first aerial photography of most glaciers postdates 1945. Several of these early sources show glaciers close to their Little Ice Age maximum positions.

BIOLOGICAL TECHNIQUES

The most useful dating tools for this timeframe are biologically based; namely dendrochronology and lichenometry. The basic principles of both have been discussed many times (*e.g.* LAWRENCE, 1950; HEUSSER, 1956; WEBBER and ANDREWS, 1973; LOCKE *et al.*, 1979; PORTER, 1981; BRADLEY, 1985; INNES, 1985). This discussion will focus briefly on the potential error terms involved.

(a) Dendrochronology

McCARTHY (1985) has recently reviewed potential errors in tree-ring dating of moraines. Apart from errors involved in coring above the base of the tree and missing the pith, the major potential errors arise from the determination of appropriate ecesis times and the assumption that the oldest surviving tree has been sampled. The probability of coring the oldest tree is more or less inversely proportional to tree density on the moraine. There are no foolproof criteria for locating the oldest tree on a surface although tree size, morphology, branch spacing and bark characteristics may be useful. In many glacier forefields tree growth may be more strongly controlled by moisture availability than age. An extreme example may be cited from the forefield of the Penny Glacier in the Premier Range, B.C. Xeric, exposed sites on moraines in the centre of the valley (*ca.* 1500-1550 m.a.s.l.) below the glacier had 77 year-old trees which were only 0.92 m tall and 3.8 cm basal diameter. However, in a sheltered wet site on the distal slope of a lateral moraine of similar age and elevation, trees in excess of 40 m high and 90 cm basal diameter were only 84 years old! Less extreme contrasts can be seen on many moraines. In addition to these spatial differences in growth environments on the moraines, differences in the ages of trees on moraine surfaces may become less apparent as the vegetation matures. The oldest trees may have been strongly suppressed initially and subsequently outgrown by later juvenile trees (see LUCKMAN *et al.*, 1984b). Although outwardly similar, the only difference might be that the older trees have 1-2 cm of very tight rings at the pith which are easily missed when coring a large tree.

Ecesis estimates have previously been made in several studies in the Rockies (Table I), usually by determining tree ages at known former ice-front positions. Average figures are *ca.* 10-20 years with smaller values at very wet sites. However, such studies rarely replicate conditions that existed during colonisation of the oldest moraine. Ice-fronts identifiable from documentary sources invariably postdate 1900 and were abandoned during the generally warmer conditions of the present century when glacier frontal positions were receding rapidly. Colonisation during the mid-late 19th or early 18th century may have been more difficult and slower. In addition, the oldest moraines at several sites investigated in the Rockies by the author are considerably coarser than later moraines and thus less favourable substrates for seedling establishment. Therefore, although these ecesis estimates may be reasonable for younger moraines, enabling dating to within ± 10 years, they may considerably underestimate ecesis on the oldest moraines.

At some localities the date of moraine formation can be estimated more precisely from trees at the trimline that have been scarred, tilted, damaged or overridden during moraine emplacement. These trees must be living (or cross-date with living trees) to provide a calendar date for the damage and the growth aberrations used should have an unequivocal glacial source. Several good examples of such dendrogeomorphic dates have been found at Athabasca and Dome Glaciers (HEUSSER, 1956; LUCKMAN, 1982, 1985, see Fig. 2). Estimates of ecesis may be derived by comparing dendrogeomorphic dates from the trimline with the oldest tree growing on these moraines. However, such estimates are maxima because of the potential lag time between moraine emplacement and stabilization of its surface following glacier recession.

In these and other cases where independent evidence is available to verify the age of tree-ring dated outer moraines, the ecesis periods may be much longer than those derived from more recent dated ice-front positions. The three ecesis estimates of this type in Table I are only a small sample but they indicate that on moraines with a sparse tree cover (due to microclimate and/or blocky substrates in these examples) ecesis values may be double or triple those from studies of inception period closer to present ice margins.

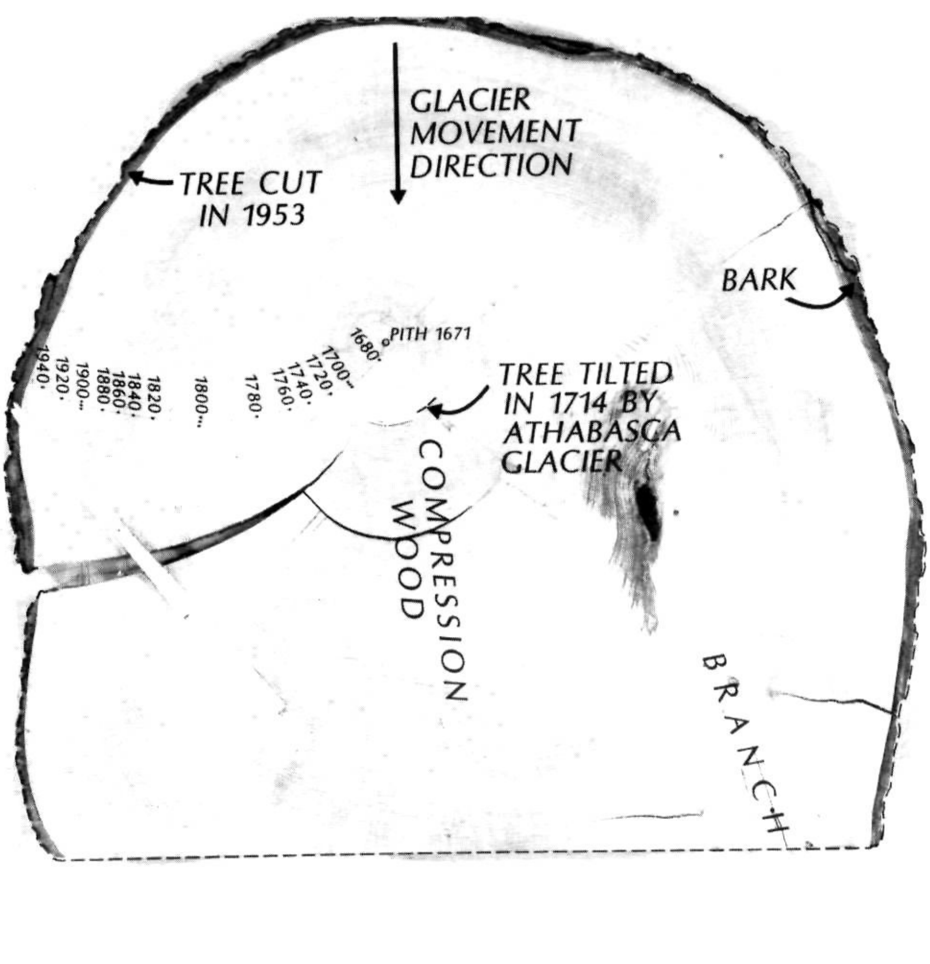

FIGURE 2. Cross section of the "Heusser Log", Athabasca Glacier. This spruce tree, situated adjacent to the western Little Ice Age lateral was tilted by the early eighteenth century advance of the Athabasca Glacier. This sample was cut by C. J. Heusser in 1953. Note the marked reduction in ring width on the annotated radius from 1820-1900 corresponding to the last major advance of the Athabasca Glacier.

Coupe du tronc d'arbre de "Heusser", glacier d'Athabaska. Cette épinette, située près de la partie ouest de la moraine latérale du Petit Âge glaciaire, a été inclinée par le glacier d'Athabaska au cours de son avancée, au début du XVIII^e s. Cet échantillon a été recueilli par C. J. Heusser en 1953. À remarquer le net amincissement des anneaux de 1820 à 1900, qui correspond à la dernière avancée importante du glacier d'Athabaska.

TABLE I

Ecesis estimates from glacier forelands in the Canadian Rockies and adjacent areas

Site	Source	Ecesis Estimates	Technique/Comment
12 sites (Rockies)	Heusser, 1956	12-17 yrs.	– photographs
Canadian Glacier, B.C.	Bray & Struik, 1963	28 yrs.	– not specified
Mount Edith Cavell	Luckman, 1977	10-15 yrs. 20-30 yrs.	– favourable sites, old photos – xeric sites, old photos
Bennington Glacier	McCarthy, 1985 McCarthy, 1985	15 ± 2 c80 yrs.	– ice fronts dated from aerial photos – oldest very blocky moraine – comparison tree & lichen dates
Tête Glacier, Premier Range	Kelly, 1985	14 ± 1	– ice front dated from air photos
Athabasca Glacier	Luckman, unpub.	c40 yrs.	– difference between dendrogeomorphic date and oldest tree on outer moraine
Dome Glacier	Luckman, unpub.	c70 yrs.	– difference between dendrogeomorphic date and oldest tree on outer moraine

Ecesis period may be defined in several ways. As used here it is considered to be the time period between exposure of the substrate and the earliest ring at the lowest point which can be cored on the tree. Studies by McCARTHY (1985) and KELLY (1985) indicate growth rates are rarely less than 2 cm/yr for seedlings in these environments and therefore the correction for differences in coring height is usually small.

These considerations suggest that the dates of the outer moraines in the sequence are subject to larger errors than later moraines. Where moraines are densely forested the oldest trees may be missed or indistinguishable whereas a sparse tree cover implies that conditions were, and continue to be, unfavourable for colonisation due to the nature of the substrate or exposed environment and therefore ecesis may be underestimated. Neither of these errors can be easily estimated without independent corroborative evidence of the age of the moraines (*e.g.* by lichenometry or dendrogeomorphic evidence).

(b) Lichenometry

Lichenometry has been used by a number of authors to date moraines and rock glaciers in the Canadian Rockies: the principal species used have been *Rhizocarpon* sp. (LUCKMAN, 1977; LUCKMAN and OSBORN, 1979; BEDNARSKI, 1979; LEONARD, 1981; KEARNEY, 1981; McCARTHY, 1985), *Xanthoria elegans* (OSBORN and TAYLOR, 1975), *Psuedephebe miniscula* (Nyl. ex Arn.) Brodo and D. Hawks. (formerly *Alectoria miniscula*, McCARTHY, 1985), and *Lecida atrobrunea* (LEONARD, 1981). The application of lichenometry in the Canadian Rockies is limited by substrate because neither *Rhizocarpon* nor *Psuedephebe* are found on carbonate rocks which are the dominant lithology in many areas.

Rhizocarpon sp. has attracted the greatest attention. However several species of yellow-green *Rhizocarpon* are present and have been identified as *Rhizocarpon geographicum (L.) DC, R. grande, R. diasporum (Naeg-ex-Hepp) Mull. Arg., R. macrosporum Ras.* (identifications by C. D. Bird, University of Calgary) and *R. inarense (Vain.) Vain* (identification by P. Y. Wong, National Museum of Canada). As several of these are often indistinguishable in the field it seems likely that the growth curve published by LUCKMAN (1977) is for *Rhizocarpon* "species" rather than simply *Rhizocarpon geographicum*. McCARTHY (1985) has developed an independent growth curve for *Rhizocarpon* sp. at the Bennington Glacier which, for the first 100-150 years, is very similar to the curve developed by LUCKMAN (1977). The curve for *Pseudephebe miniscula* (McCARTHY, 1985) indicates that this lichen has a much faster growth rate than *Rhizocarpon* sp. and so it is only useful for the youngest moraines and first 100 years of growth.

At many sites, particularly above tree-line, lichenometry is the only absolute dating technique possible. However, more and better control points are needed to provide a regional growth curve for the Canadian Rockies. Presently there is only a single control point beyond 200 years (LUCKMAN, 1977) and extrapolation beyond this point provides only minimum dates. Nevertheless, despite potential difficulties with the presence of different *Rhizocarpon* species (see INNES, 1982), lichenometry will continue to provide good chronological control for dating Little Ice Age events in this area and a valuable cross-check on minimum ages determined by tree-ring dating.

CARBON 14 DATING

Variation in the abundance of atmospheric ^{14}C over the last 1000 years has resulted in a non-linear relationship between calendar years and radiocarbon years (see PORTER, 1981; STUIVER, 1982; BRADLEY, 1985). As a result the range of possible calendar date equivalents for a ^{14}C date in this timeframe is often greater than the radiocarbon error term (see Fig. 3) or may produce multiple calendar equivalents for a single ^{14}C date (see PORTER, 1981). Therefore ^{14}C dating does not have sufficient precision to be a primary dating technique for the Little Ice Age, even if specimens are available, and is useful only to give an indication of the general age of the specimen, *e.g.* whether an overridden tree is 100, 700, or 4000 years old. In several cases (see below) there are

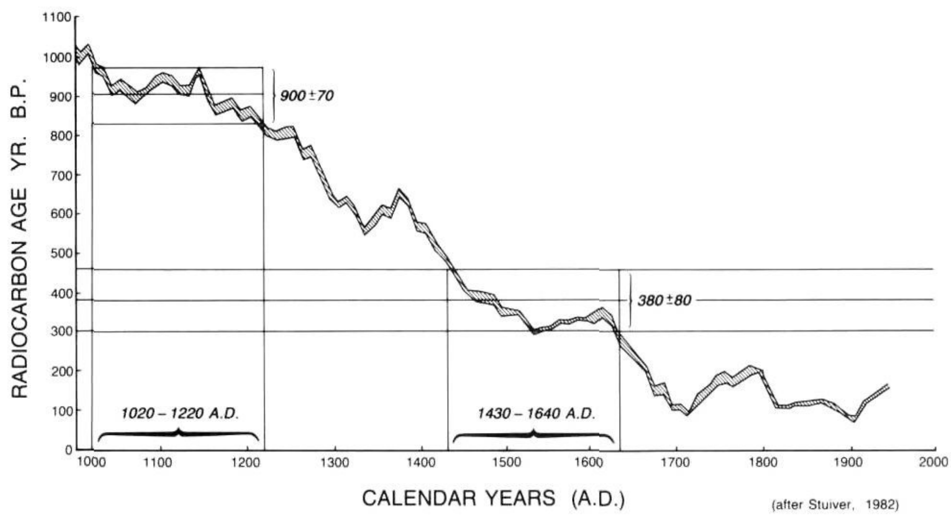

FIGURE 3. Relationship between ^{14}C age and calendar years from 1000-1950 A.D., The diagram is based on STUIVER (1982). The conversion of ^{14}C error terms to calender equivalent dates is shown for two ^{14}C dates from Bennington Glacier (see Table III).

Relations entre les dates au radiocarbone et celles du calendrier de 1000 à 1950 ap. J.-C. (diagramme fondé sur STUIVER, 1982). On fait ici la conversion des écarts des dates ^{14}C aux dates du calendrier équivalentes à l'aide de deux datations provenant du glacier de Bennington (voir le tabl. III).

inconsistencies between ^{14}C dates and tree-ring dates from cross-dated trees.

DISCUSSION

In dating Little Ice Age sequences reliance is usually placed on a single technique because multiple lines of evidence are not available. Each technique has potential error terms which are often ignored when they cannot be calculated and multiple dating criteria should be used as a cross-check whenever possible. Complementary lichenometry and tree-ring studies on moraines in the Rockies are generally limited to those sites with moraines below tree-line and a siliceous substrate. The potential errors involved in relying on a single technique can be illustrated by the example of the Bennington Glacier, British Columbia (McCARTHY, 1985). This alpine glacier is 4 km long and situated immediately west of the Continental Divide. The outer Little Ice Age moraine includes many large blocks of quartzite which were bulldozed into the forest. In addition to lichenometry and tree-ring dating, the age of this moraine can be estimated from ^{14}C dates on overridden trees beneath the outer moraine and dendrogeomorphic evidence from a large standing snag rooted immediately outside this moraine. This tree shows a period of extreme growth suppression for the whole radius of the tree for a 45 year period ending some 80-90 years before the tree's death. Although this site appears ideal for demonstrating the use of multiple dating criteria, each of these lines of evidence produces a different date for the emplacement of the moraine which range from 1475 to 1719 (Table II).

Given the blocky nature of the moraine and sparse tree cover, the tree-ring date is clearly an underestimate, but differences between the other dates cannot presently be resolved. It is hoped that work in progress which is attempting to cross-date the snags and buried trees with old living trees at the site will provide a more conclusive answer.

CHRONOLOGY OF LITTLE ICE AGE GLACIAL ADVANCES IN THE CANADIAN ROCKIES

Figure 4 presents the available data for dated moraines in the Canadian Rockies between 1500 and 1925 A.D. It is based, with some minor revision, on the data from LUCKMAN and OSBORN (1979, Table II) plus North Cirque Rock Glacier, Whistlers Creek (BEDNARSKI, 1979); Center Glacier, Mary Vaux Glacier and the Brazeau Icefield (KEARNEY, 1981); Crowfoot Glacier, Balfour Glacier and the Wapta Icefield (LEONARD, 1981); Bennington Glacier (McCARTHY, 1985); and Berg Glacier, Mount Robson (LUCKMAN *et al.*, 1984a). Most of the data from the 33 glaciers are based on dendrochronology or lichenometry.

Despite differences in techniques and possible error terms, a general pattern emerges from these data. Three major periods of moraine building may be recognised. Firstly, over 30% of the glaciers sampled show outer moraines dated to the first quarter of the eighteenth century. A second group show outer or readvance moraines dating from the nineteenth century that are close to or overrode the eighteenth century positions. At many sites there is a sequence of well-defined, closely spaced moraines which are dated between 1825 and 1925 and are the most conspicuous feature of Figure 4 (see also LUCKMAN and OSBORN, 1979, Table 2). These two major pulses (early eighteenth century and mid-late nineteenth century) are well-defined, show synchroneity between several sites and appear to reflect the culmination of two major periods of glacier advance. The remaining 30% of the glaciers have outermost moraines dated between 1500-1700 A.D. with few coincident dates. Half of this group of moraines are dated by dendrochronology and half by minimum lichenometric dates beyond the calibrated range of the Cavell growth curve (LUCKMAN, 1977) but with lichen sizes which are too small to be considered Crowfoot equivalent (see LUCKMAN and OSBORN, 1979). In several cases the moraines are fragmentary and partially overridden by younger moraines. This group of dated moraines certainly represent earlier Little Ice Age advances but it is not clear whether the differences in age within this group are real or simply reflect poor dating control on a series of moraines from one or two major advances. There is also one glacier (Dungeon Peak, Jasper National Park, LUCKMAN and OSBORN 1979) which has an extrapolated lichenometric age for the oldest moraine fragment of 1355 A.D.

TABLE II

Dating scenarios for the outermost moraine at Bennington Glacier

Technique	Best estimate
1. TREE-RING DATING Oldest tree on moraine 1721 + 3 years = 1718 (for coring height) (germination date) Other trees (earliest rings) 1738, <1749, 1756, 1785, 1795	1718 A.D. – ecesis pediod
2. LICHENOMETRY Largest *Rhizocarpon* sp. lichens 72, 72, 70, 70, 70 mm Estimated age extrapolating growth rate of 11.4 mm/century from LUCKMAN'S (1977) oldest point at Mount Edith Cavell 1712 ± 12 = 62 mm lichen $10 \text{ mm} = \frac{10}{11.4} \times 100 \text{ yrs} = \text{c}90 = 1622 \pm 15$	1622 ± 15 A.D.
3. OVERRIDDEN TREES ^{14}C date 380 ± 80 yr BP (Beta 9659) Calendar year equivalent (STUIVER, 1982) = 1430-1640 A.D. Date is from rings 1-20: Tree has 135 rings For killing date add 110 yrs = 1540-1750 A.D.	1540-1750 A.D.
4. LARGE DEAD SNAG WITH GROWTH SUPPRESSION JUST OUTSIDE TERMINAL (A) SUPPRESSION (B) TREE DEATH ^{14}C date 900 ± 70 ^{14}C yr BP (Beta 12417) Calendar year equivalent (STUIVER, 1982) = 1020-1220 A.D. Assume date is equivalent to ring 10 (rings 1-16 dated) Period of major growth suppression rings 366-409 (A) Death of tree = ring 481 (B) Equivalent calendar dates (add 355 (A) or 471 (B)) Suppression 1375-1575; death 1491-1691 A.D.	 1375-1575 A.D. 1491-1691 A.D.

Based in part, on McCARTHY, 1985

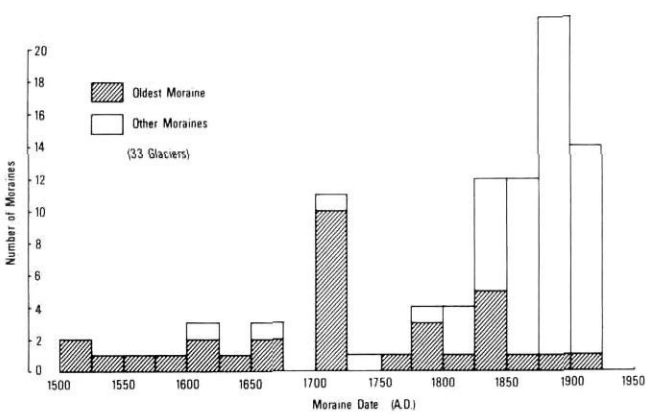

FIGURE 4. Dates of Little Ice Age moraines between 1500-1925 A.D. in the Canadian Rockies (for sources see text.)

Datations de moraines du Petit Âge glaciaire entre 1500 et 1925 ap. J.-C. dans les Rocheuses du Canada (voir le texte).

INCEPTION OF THE LITTLE ICE AGE

The data reviewed above suggest two well defined periods of moraine building during the Little Ice Age in the early eighteenth and nineteenth centuries. There is also more fragmentary evidence of older moraines with less secure dating control that represent earlier Little Ice Age advances. These earlier advances were presumably overridden by subsequent, more extensive events at the majority of sites. Additional evidence for the early history of the Little Ice Age has been found at four other sites which will now be discussed in more detail.

ROBSON GLACIER

During his investigations in 1953, HEUSSER (1956) discovered a buried spruce forest which had been overrun during the Little Ice Age by the Robson Glacier and was exposed in stream sections about 400 m upvalley of the terminal moraines. He obtained a ^{14}C date of 450 ± 150 ^{14}C yr BP which was used to indicate the beginning of his "Late-Postglacial Ice Maximum". Resampling of this site indicates that this buried forest horizon outcrops in several abandoned proglacial channels which are entrenched 2-3 m into the Robson Glacier forefield south of the present river. The former channel floors and downstream fans are littered with over a hundred logs up to 0.35 m in diameter derived from this material. In addition, tree stumps in growth position protrude from the till surface at a few localities on the interfluves between channels (Fig. 5). Several stumps show incontrovertible evidence that they were sheared in growth position (Fig. 6) and a thin paleosol, with rooted trees, is exposed in at least three localities. The exposed forest layer lies at depths ranging from 0.5 to about 3 m below the present till surface and is developed on a fine-grained gray till which appears identical to the Little Ice Age till. No volcanic glass shards were found in the fine sand fraction of two samples from the buried organic horizon (YOUNG, 1985). It is therefore possible that the underlying till may be Neoglacial in age.

Radiocarbon dates have been obtained from three additional trees at this site (Table III). All three dates are considerably older than Heusser's early date and suggest the trees were overridden in the late twelfth or thirteenth century. There is a 52 year overlap (1153-1205 A.D.) in the estimated killing dates from the new ^{14}C dates (Table III) but a precise date cannot be given until one or more of these trees has been cross-dated with an existing tree-ring chronology.

These new ^{14}C dates indicate that the Robson Glacier had advanced to a position within 400 m of its Little Ice Age maximum position by *ca.* 1150-1250 A. D. HEUSSER (1956) considered that, based on cores from 8 trees and a 12 year ecesis period, the outermost moraine at Robson Glacier was first colonized in 1783 and cites no morphological evidence of an earlier advance. Therefore, either the deposits of the twelfth/thirteenth century advance were subsequently overridden by the advance which formed the major moraines in the 1780's or the glacier was within 400 m of its Little Ice Age maximum position from the 12th/13th-18th centuries.

KIWA GLACIER

The Kiwa is the longest glacier in the Premier Range, immediately west of the Rocky Mountain Trench and about 50 km SW of Robson Glacier (Fig. 1). The glacier is 9 km

TABLE III

Calendar equivalents of ^{14}C dates for the initial "Little ice Age" advance at Robson and Kiwa Glaciers

Sample	# Rings	Rings dated	^{14}C Date	Calendar equivalent*	Correction for ring position	Estimated range for killing date (A.D.)
ROBSON FOREFIELD						
Heusser (1956)	135	N.A.	450 ± 150	1320-1360 1390-1640	the tree died at 450 ± 150 (p. 276)	1320-1360 1390-1640
R80-2S	126	1-15	860 ± 50 (B2816)	1020-1090 1120-1230	+ 115 yr	1135-1205 1235-1345
R81-6S†	186	136-156	900 ± 60 (B3731)	1020-1215	+ 40 yr	1060-1255
R81-5S	428	48-63	1140 ± 80 (B9458)	780-980	+ 373 yr	1153-1353
KIWA GLACIER, PREMIER RANGE						
K84-1†	c100	1-30	840 ± 80 (B12416)	1040-1100 1120-1140 1160-1270	+ 80 yr	1120-1180 1200-1220 1240-1350

All dates are from overridden trees.
* Based on STUIVER (1982) Figure 3: multiple dates occur because the calibration curve is not linear.
† In growth position.
N.A. = not available.

FIGURE 5. Standing snag protuding through Little Ice Age till in the forefield of the Robson Glacier. The snag is about 60 cm long (August 1981).

Souche debout dans la moraine du Petit Âge glaciaire dans la partie antérieure du glacier de Robson. La souche mesure 60 cm de long (août 1981).

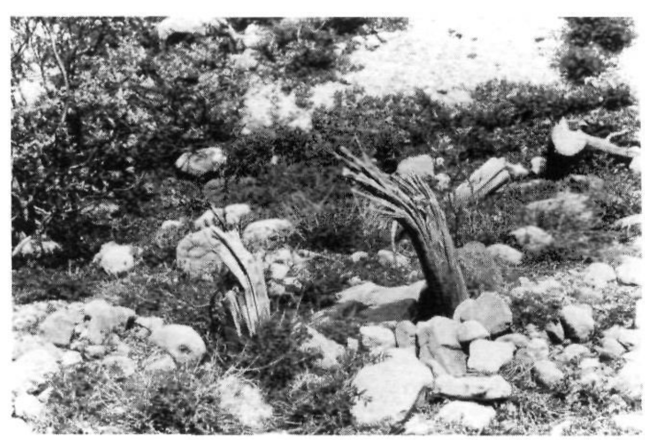

FIGURE 6. Sheared snags exposed in the bed of an abandoned pro-glacial stream in the Robson Glacier forefield. The lens-cap (center) is 5.5 cm diameter. The channel bank behind this tree is in till, glacier flow was from right to left (August 1981).

Souche arrachée reposant sur le lit abandonné d'un courant proglaciaire dans la partie antérieure du glacier de Robson. Le capuchon de lentille au centre mesure 5,5 cm de diamètre. La berge du chenal derrière l'arbre est constituée de matériel morainique; l'écoulement se faisait de droite à gauche (août 1981).

long and terminates in a glacial lake at *ca.* 1460 m.a.s.l. (Fig. 7). The oldest tree on the outermost Little Ice Age moraine, 1.5 km downvalley of the present snout, indicates that this moraine was formed about 1750-1760 (WATSON, 1986). A tree stump about 9 cm in diameter was found protruding from the till surface about 100 m downvalley of the present snout *ca.* 5-7 m above lake level. The tree appeared to be in growth position and yielded a radiocarbon date of 840 ± 80 yr BP from the first 30 rings indicating it was probably killed between 1150-1350 A.D. (Table III). Evidence at both the Kiwa and Robson sites indicates a glacier advance over trees on the present valley floor to within 0.4 km (Robson) or 1.4 km (Kiwa) of the Little Ice Age limit in the 12th, 13th or 14th centuries. Although the Little Ice Age moraines downvalley are substantial, the till burying these trees is only 1-2 m thick at both sites.

HECTOR LAKE

LEONARD (1981, 1986a, 1986b) has carried out studies of the sedimentation record in Hector Lake in Banff National Park, about 85 km south-south-west of the Columbia Icefield. Most of the sediment entering the lake comes from the Balfour Stream, a small drainage basin which is 41% glacierized and contains the Hector and Vulture Glaciers and part of the Waputik Icefield. The varve record recovered from this lake spans the last 800 years and shows strong correlations between sedimentation rates and periods of moraine formation during the eighteenth and nineteenth centuries. LEONARD (1986b) identifies five major periods of high sedimentation rates, namely 1240-1250, 1600-1650, 1700-1735, 1825-1885 and 1920-1950. With the exception of the latest high sedimentation phase {which reflects the period of maximum twentieth century glacier recession (GARDNER, 1972; LEONARD, 1986b)}, Leonard considers that these high sedimentation rates correspond with periods of increased ice cover in the Balfour basin. LEONARD (1981) therefore postulated that the high sedimentation rates near the base of the Hector core indicated a glacial advance in the early thirteenth century. The subsequent radiocarbon dates from Robson and Kiwa Glaciers indicate a correlative glacier advance at these sites in the twelfth or thirteenth centuries (see LEONARD, 1986b, Fig. 9). Given that these sites are widely separated and quite different in their glacier characteristics, this broad synchroneity suggests that the advance was probably regional in extent.

FIGURE 7. Ice-front, pro-glacial lake and Little Ice Age morainic complex of the Kiwa Glacier, Premier Range, B.C. The site of the overriden tree is indicated by the arrow (July 1984).

Front glaciaire, lac proglaciaire et complexe morainique du Petit Âge glaciaire, glacier de Kiwa, première chaîne, C.-B. La flèche montre le site de l'arbre renversé (juillet 1984).

COLUMBIA ICEFIELD (ATHABASCA GLACIER)

Dendrogeomorphic evidence at the Athabasca Glacier indicates the main Little Ice Age advances were in 1714 and *ca.* 1840-50 (HEUSSER, 1956; LUCKMAN, 1985). In both events the ice terminated at the foot of a long south-facing slope flanking Mount Wilcox (Fig. 8). This slope has a patchy tree cover and studies of seedling establishment suggest the present tree-line is advancing (KEARNEY, 1982). A large number of dead snags and rootstocks are scattered over the slope (Figs. 9, 10). Many of these are larger than trees presently growing on the slope and reach maximum dimensions of over 60 cm diameter and 10 m long (probably originally 20-30 m high). The size and growth habit of these snags suggest that they grew under more favourable conditions than the present trees and that tree-line regressed in this area prior to the present tree-line readvance.

Although many of these snags are rotten or hollow, sections have been cut from over 80 sound trees. Radiocarbon dates from three of these trees indicate that they could have died within 50 years of each other between 900-1100 A.D. (samples A80-A1C, A80-D2, A80-E, Table IV). A radiocarbon date from a sequence of 7 very wide (4-5 mm) juvenile rings from a *Pinus albicaulis* yielded a somewhat younger ^{14}C date of 940 ± 80 yr BP (1010-1160 A.D.).

FIGURE 8. Little Ice Age moranic complex of the Athabasca Glacier and the lower slopes of Mount Wilcox, view N.W., July 1984. The large dead snags occur on the sparsely vegetated slopes beyond the two buildings (centre, left) and extend to the upper limit of present vegetation seen on that slope. The stand containing the old *Picea englemannii* is indicated by the arrow.

Complexe morainique du Petit Âge glaciaire au glacier d'Athabaska et les pentes inférieures du mont Wilcox (vue vers le N-O, juillet 1984). Derrière les deux bâtiments (au centre et à gauche), on trouve de grosses souches mortes sur les pentes recouvertes d'une végétation éparse et même du delà de la limite actuelle de la végétation que l'on voit sur le versant. La flèche montre le peuplement où se trouve le vieux Picea englemannii.

FIGURE 9. Large snag on the upper part of the Mount Wilcox slope. This tree was too rotten to sample or date and occurs close to the present limit of tree growth on the slope (August 1978).

Gros tronc reposant sur la partie supérieure du versant du mont Wilcox. Cet arbre, trop pourri pour l'échantillonnage ou la datation, est situé près de la limite de croissance des arbres sur le versant (août 1978).

At the base of the Mount Wilcox slope and immediately west of the terminal moraines of the Athabasca Glacier is an isolated stand of subalpine forest containing a large number of old trees (Fig. 8). This stand contains the oldest living *Picea englemannii* known in Alberta (680 years old at breast height, LUCKMAN *et al.*, 1984b; JOZSA *et al.*, 1983) and a tree-ring chronology has been developed at this site that extends back to 1323 A.D. (JOZSA *et al.*, 1983). Ringwidth and densitometric studies have been carried out on 12 snags sampled from the Wilcox slope. The ring-width and density patterns from 8 of these trees may be cross-dated with either the 659-year living-tree chronology or with a "floating" chronology of 308 years from snag A80-A1C which covers the period *ca.* (950-1230) ± 65 ^{14}C yr BP (Table V).

Two trees were cross-dated with the floating master chronology (A80-A1C) indicating that all three trees died within a 30 year period. A78-S2 was identified (by Forintek Canada Corporation, Vancouver) as *Larix* (probably *Larix lyallii*) and is the only larch tree ever found in Jasper National Park. The northernmost larch recorded during the recent Biophysical Inventory of Banff and Jasper National Parks (HOLLAND and COEN, 1982) was an isolated individual in Clearwater Pass (50°44'N, 116°15'W, P. Achuff, pers. comm., 1981). Therefore the larch tree growing at the Columbia Icefield *ca.* 1000-1250 A.D. was approximately 90 km N.W. of the present northern limit of the species.

The other cross-dated tree (A80-D2, *abies*) has also been radiocarbon dated. It is interesting to note that the dendrochronological cross-date reverses the position of the two ^{14}C dates (Table IV): the 1065 ± 65 ^{14}C date comes from rings 170-200 on A80-A1C but the 1110 ± 65 ^{14}C date from A78-S2 comes from cross-dated rings equivalent to rings 246-281 on sample A80-A1C. Five other trees have been successfully cross-dated with the living-tree chronology. Although they lived for different lengths of time, four of the five trees began growth in the fourteenth century and all died in a forty year period (1656-1696 A.D.) immediately prior to the early eighteenth century advance of the Athabasca Glacier (Fig. 2).

On the basis of the ^{14}C dates and cross-dating completed to date there appear to be two distinct populations of snags on this slope; an older group which grew between *ca.* 700-1250 A.D. (only A78-S1 lived beyond 1100 A.D.) and a younger group which lived between *ca.* 1300-1700 A.D. The large error ranges associated with the ^{14}C dates produce some

FIGURE 10. Spruce snag (A80-A1C) on the Wilcox slope, Columbia Icefield. A ^{14}C date of 1065 ± 65 yr BP has been obtained from this tree which has 308 rings. Note the size of the snag relative to the present trees on the slope and the attached rootstock indicating the tree is close to its growth site. View to the south, July 1981, showing the Banff-Jasper Highway, Sunwapta Lake (right) and the Athabasca Glacier (top) in the distance.

Souche d'épinette (A80-A1C) sur le versant du mont Wilcox, champ de glace Columbia. La datation au radiocarbone de 1065 ± 65 a été obtenue à partir de cet arbre qui comprend 308 anneaux. À remarquer la taille de la souche par rapport aux arbres vivant sur le versant et les racines qui montrent que l'arbre est près de son lieu de croissance. Cette vue vers le sud permet de voir la route Banff-Jasper, le lac Sunwapta (à droite) et le glacier d'Athabaska (en haut) au loin (juillet 1981).

TABLE IV

Radiocarbon dates from snags near treeline at the Columbia Icefield Chalet

Sample #	Species	Rings	Rings dated	^{14}C Date	Calendar equivalent	Correction for tree death	Death date (calendar years)
A80-A1C	*Picea*	308	170-200	1065 ± 65 (B1829)	890-1000	+ 120	1010-1120 A.D.*
A80-D2	*Abies*	198	163-198	1110 ± 65 (B1830)	780-790	+ 20	800- 810 A.D.*
					860-980		880-1000 A.D.*
A78-S1	*P. albicaulis*	105	10-17	940 ± 50 (GSC2806)	1010-1160	+ 90	1100-1250 A.D.
A80-E1	*Pinus?*	118	50-75	1050 ± 85 (B1828)	725-1040	+ 40	765-1080 A.D.

* These two samples have been successfully cross-dated (see Table V). The cross-date indicates A80-D2 died 27 years before A80-A1C i.e. the ^{14}C date of A80-A1C should be about 100 years older than A80-D2.

TABLE V

Cross-dated snags from near treeline at the Columbia Icefield Chalet

Sample #	Species	Total rings	Equivalent on master	Difference in death date from master
(i) *Floating*				
A80-A1C	*Picea*	308	1-308*	0
A80-D2	*Abies*	198	90-281	−27
A78-S2	*Larix*	161	128-289	−19
(ii) *Successfully crossdated with living trees*				
A82-204	*Picea*	680	1323-1981**	
A81-7S	*Picea*	295	1391-1687	
A81-11S	*Abies*	381	1315-1696	
A81-13S	*Picea*	327	1339-1666	
A82-2S	*Abies*	281	1375-1656	
A82-3S	*Abies*	251	1446-1695	

All cross-dates were obtained from indexed ring-width and maximum density data at Forintek Canada Corporation, Vancouver, using their Shifting Unit Dating Program. This work was carried out by L. Jozsa and P. Bramhall.

* "Floating Master" Chronology

** Oldest living tree in the 659 year chronology developed by JOZSA *et al.* (1983)

overlap but it appears that these two periods bracket the glacial advance identified at the Robson, Kiwa and Hector sites. The earlier phase overlaps the timing of the Little Climatic Optimum (Early Medieval Warm Period, LAMB, 1977) of Western Europe. The presence of larch north of its present range and the large snags at the Icefield site certainly suggest conditions were more favourable for tree growth at that site 700-1100 years ago than they were in the past few centuries. On the basis of sedimentation rates and other evidence LEONARD (1986b) considers the period 1300-1600 A.D. to represent warmer conditions. It is therefore possible that the younger snags at the Icefield site may represent a phase of tree-line advance following the 12th/13th century glacial event and which was terminated by severe conditions of the late seventeenth/early eighteenth centuries.

DISCUSSION AND CONCLUSION

The evidence from the four sites discussed above presents a reasonably consistent and complementary picture of changing environmental conditions over the last thousand years in the Canadian Rockies. During the period *ca.* 700-1100 A.D. tree-line was higher than present at the Columbia Icefield and conditions were probably warmer based on the presence of alpine larch north of its present range and the growth morphology of the snags found. Mature forest was growing at the Robson and probably Kiwa Glaciers on sites which have been deglaciated within the last 50-60 years. By 1150-1250-A.D. glaciers had advanced to within 1400 m (Kiwa) or 400 m (Robson) of their Little Ice Age maximum limits and there was a synchronous advance of glaciers draining into Hector Lake (LEONARD, 1986b). Lower sedimentation rates at Hector Lake and recolonisation of slopes at the Columbia Icefield site suggest a more favourable climate during the 14th-16th centuries. Glacier advances have been recognized from a number of sites in the 16th and 17th centuries but dating control is relatively poor. The most extensive Little Ice Age glacial advances occurred in the early 18th and mid-late 19th centuries at most sites investigated.

This scenario is tentative because of the limited number of sites investigated, the poor dating resolution of ^{14}C and small amounts of other proxy climate data in this timeframe. Available palynological records typically have sedimentation rates of 100-300 years/cm (*e.g.* KEARNEY and LUCKMAN, 1983) and therefore have inadequate temporal resolution for detailed studies of the last 1000 years. However, two recent studies in the Canadian Cordillera have noted evidence of significant glacial advances *ca.* 550-900 ^{14}C yr BP (see also discussion in PORTER, 1981). RYDER and THOMSON (1986) consider a major ice advance began in the Coast Mountains of British Columbia about 1000 BP. Three sites indicate significant early expansion of glaciers; glaciers overrode a paleosol, ^{14}C dated at 835 ± 45 yr BP, at the Franklin Glacier, a tree stump dated at 900 ± 40 yr BP at the Klinaklini Glacier, and tree stumps dated at 540 ± 45 and 680 ± 50 yr BP at the Bridge Glacier. OSBORN (1984, 1986) working at the Bugaboo Glacier, just west of the Rocky Mountain Trench, also postulates a period of glacier advance beginning shortly after 900 ^{14}C yr BP. It therefore appears likely that the Little

Ice Age glacial advances in the Canadian Rockies began in the 12th or 13th centuries at many sites. At present there is no conclusive evidence to indicate whether the 17th-19th century maximum downvalley positions are the culmination of the 12th-13th century advance or separate, later events. However the tree-line fluctuations at the Athabasca site and LEONARD's (1986b) sedimentation rate data support the inference that the glaciers receded following the 12th-13th century advances and these deposits were overridden by more extensive advances in the 17th-19th centuries.

The record presented above is incomplete and more, better dated sites are needed to improve the chronological control for these early Little Ice Age events. However, given that the glacial record is by its nature incomplete, there is a need to expand the record from other types of proxy data. The two most promising sources are varved lake sediments and tree rings because of their high temporal resolution and continuous records. Recent work has demonstrated the potential for living-tree chronologies of 4-700 years (LUCKMAN *et al.*, 1984b) and the preservation of wood on the surface at near-glacier sites which is over 900-1100 ^{14}C yrs old at Bennington Glacier and the Columbia Icefield suggests that longer chronologies can be developed by cross-dating. These have significant potential in two respects. Long chronologies in conjunction with successful cross-dating can be used to provide more precise dates from buried trees or snags associated with glacier fluctuations. Secondly, if appropriate techniques can be developed (see LUCKMAN *et al.*, 1985), these records may also provide proxy climatic data over the same timeframe. LEONARD's work (1981, 1986a, b) has demonstrated the potential for recovering sedimentation records with similar temporal resolution and length from lacustrine deposits. Further work is needed to explore records of this type at other sites and to examine the relationships between glacier fluctuations and sediment accumulation patterns in more detail.

ACKNOWLEDGEMENTS

I would like to thank the following: for assistance in the field; F. F. Dalley (1978, 1980), A. B. Beaudoin (1978, 1982), D. P. McCarthy (1981, 1982), G. W. Frazer (1981-3), J. P. Hamilton (1983-5), K. Harding, P. Kelly, H. Watson and R. Young (1984); C. J. Heusser kindly provided the sample shown in Figure 2; Parks Canada and B. C. Provincial Parks for permission to carry out research in these areas; L. Jozsa at Forintek Canada Corporation for densitometric work; D. Biedermann, formerly of Parks Canada, Jasper, for assistance and support; and the Cartographic Section, Geography, U.W.O. for figures 1, 3 and 4. Investigations in the Canadian Rockies were supported by grants from the Natural Sciences and Environmental Research Council of Canada. Thanks are also extended to G. D. Osborn and J. M. Ryder for their useful comments when revewing this paper.

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