Age constraints for a late-glacial morainal shoal in Howe Sound, British Columbia

By

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

University of Washington

2001

Program Authorized to Offer Degree: Department of Earth and Space Sciences

University of Washington
Graduate School

This is to certify that I have examined this copy of a master's thesis by

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Abstract

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Following its initial retreat, the Cordilleran Ice Sheet readvanced into the eastern Fraser Lowland and northwestern Washington during a brief climatic interval referred to as the Sumas Stade. Similarly, after retreating from the Strait of Georgia, the Cordilleran Ice Sheet readvanced to a position near Porteau Cove, Howe Sound, where it deposited a morainal shoal. ^{36}Cl ages of glacially eroded bedrock surfaces sampled up-glacier and down-glacier from the Porteau moraine bracket the timing of deposition between 12,400 ± 500 and 10,600 ± 600 ^{36}Cl yr ago. Other studies suggest evidence for a subsequent advance near the town of Squamish, which would have occurred after 10,600 ± 600 ^{36}Cl yr ago.

On the basis of available ^{36}Cl and ^{14}C ages, the late-glacial readvance of the Cordilleran Ice Sheet into Howe Sound was broadly contemporaneous with readvances found in the central Fraser Lowland and northwestern Washington. The general agreement of the limiting ages for readvance or halt of the ice-sheet margin in two different fjord systems suggests that it could represent a regional climatic event. Though construction of the Porteau moraine falls within the European Younger Dryas interval (12,700-11,400 cal yr BP), it may be unrelated to North Atlantic cooling. Because of broad age constraints, lack of stratigraphic evidence for a readvance, and location of Porteau Cove as a natural pinning point for retreating or advancing ice prevent conclusive determination of the cause of the late-glacial readvance that deposited the Porteau moraine.

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I would like to thank Jason Briner, Nate Chutas, and Dennis McCrumb for their assistance in the field. I would like to thank the National Science Foundation ESH Grant #9632367, Geological Society of America, and Department of Earth and Space Sciences for providing the funding that made this project possible. I would like to thank Stephen Porter for his input and critique of this research project. I would like to give special thanks to Terry Swanson for his guidance and support.

Dedication

This thesis is dedicated to my family and friends.

INTRODUCTION

During the last glaciation, the Cordilleran Ice Sheet expanded southward from the Coast Range and Fraser Lowland of British Columbia into northwestern Washington. The advance and retreat history of the Puget Lobe of the Cordilleran Ice Sheet is reasonably well known from numerous radiocarbon ages of terrestrial and marine fossils that lie under, within, and over drift of the last glaciation. The initial retreat of the ice sheet was rapid (Porter and Swanson, 1998), and strongly controlled by negative mass balance, a eustatically rising sea level, and ameliorating, climate (Clague *et. al.,* 1997). By ~13,900 cal yr BP the ice sheet margin had retreated to narrow, stable calving positions at the mouths of fjords and valleys in the coastal mountains of British Columbia (Clague *et. al.,* 1997).

Following its initial retreat, the ice sheet readvanced into the eastern Fraser Lowland during a brief climatic interval referred to as the Sumas Stade (Armstrong *et. al.*, 1965). Recent work by Clague *et. al.* (1997) indicates that the Sumas Stade is represented by at least two advances of the ice sheet in the central Fraser Lowland. Radiocarbon dates limit the first readvance to before 13,900 cal yr BP and a second to after 13,200 cal yr BP (Clague *et. al.*, 1997). Kovanen and Easterbrook (in press) also propose two Sumas readvances, the first occurring between 13,200 and 12,500 cal yr BP and the second shortly before 11,400 cal yr BP, based on ages of basal peat in Sumas meltwater channels.

Two hypotheses have been proposed by Clague *et. al.* (1997) to explain the cause of the Sumas readvance(s): (a) climatic cooling that lowered the equilibrium line of the ice sheet, thereby causing the glacier to advance, and/or (b) following initial rapid retreat and subsequent grounding, the ice sheet had a positive mass balance and it readvanced at a time of falling relative sea-level resulting from rapid isostatic uplift.

To test the validity of these hypotheses, Howe Sound, B.C. (Fig. 1) was selected for study because of its proximity to the central Fraser lowland, and the presence of a moraine shoal of presumed late-glacial age. Bathymetric data indicate that the Porteau moraine, having a geographic position similar to that of Sumas moraines in the Fraser Lowland, was deposited at narrow restriction in Howe Sound (Fig. 2). It is inferred from geomorphic data that a possible second advance terminated near Squamish (Friele and Clague, in press). The main objective of the present research is to constrain the age of these two late-glacial features using calibrated radiocarbon ages of organic matter collected from ice-proximal deltaic sediment and cosmogenic ^{36}Cl ages of glacially eroded bedrock sampled both up- and down-glacier from the Porteau moraine. Age constraints of these features will enable one to evaluate whether these ice advances were controlled by climate or factors of ice dynamics.

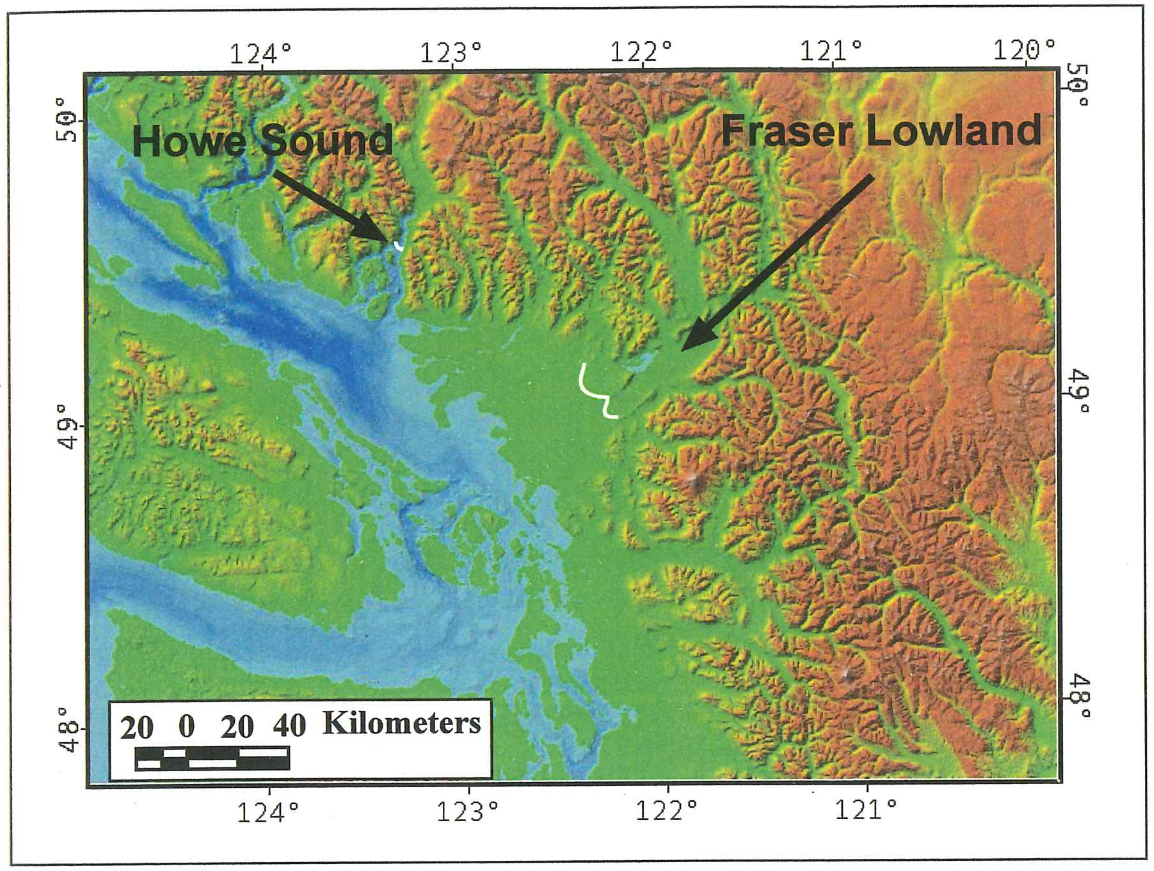

Figure 1. Map of southwestern British Columbia and northwestern Washington showing the location of Howe Sound relative to central Fraser lowland. Terminal moraine positions of late-glacial advances are shown as solid white lines in respective locations.

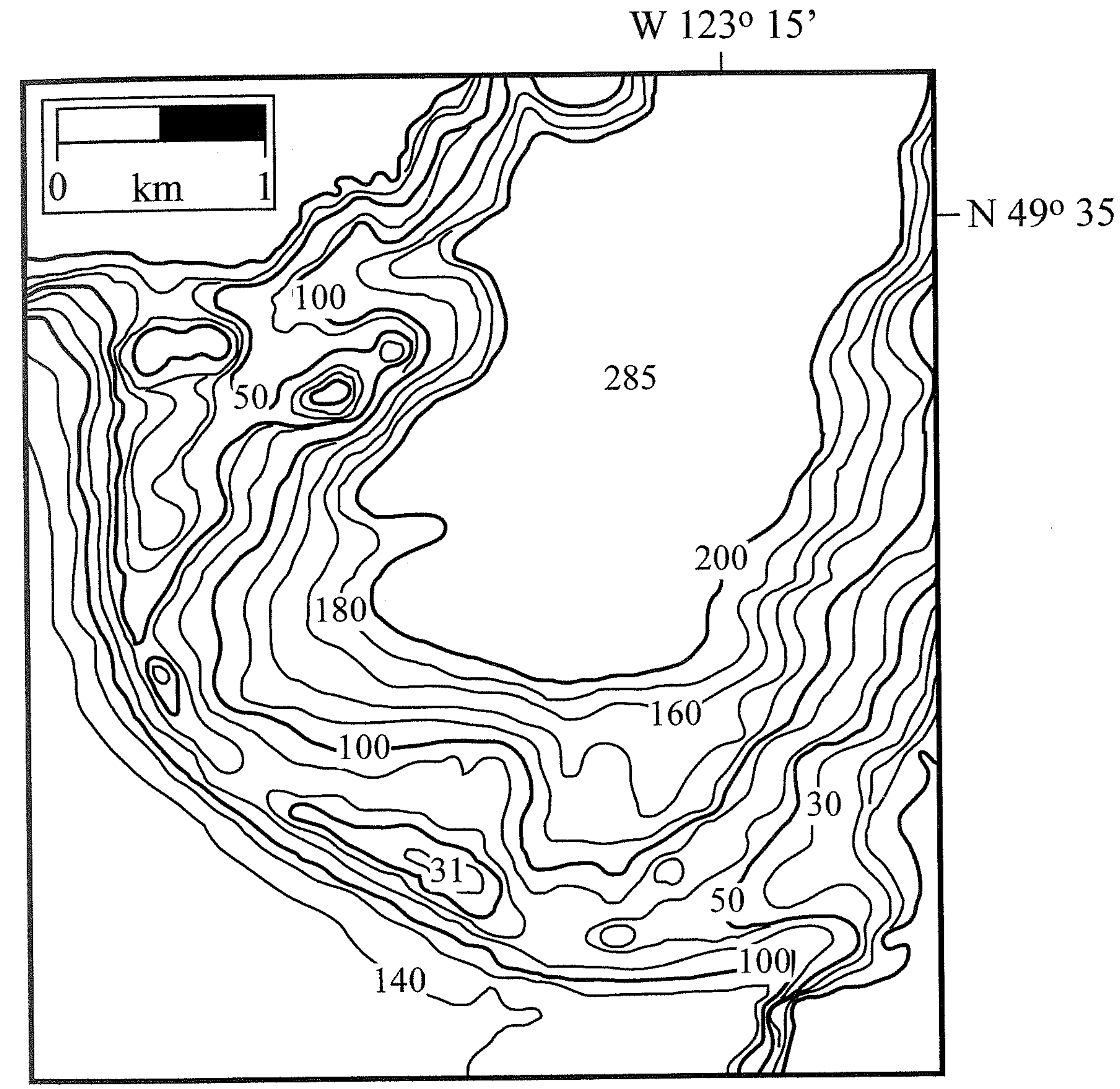

Figure 2. Bathymetric data (in meters) of a morainal shoal near Porteau Cove in Howe Sound. Map obtained from Canadian Hydrologic Survey.

Cosmogenic ^{36}Cl dating was the primary dating method used to obtain constraining ages for the deglaciation of Howe Sound. Chlorine-36 is a cosmogenic isotope produced by the interaction of cosmic rays with surface rock. The concentration of ^{36}Cl in the exposure history of a sample is determined by isotopic composition of the surface rock. Among other factors, production of the isotope within a rock is affected by the mass of the overlying material (*i.e.*, air, water, snow, *etc.*). Most geologic uncertainties can be qualitatively evaluated in the field. However, poor constraints on the depth of snow cover and timing of emergence are two potential sources for error that can affect exposure histories within the study area. To account for potential sources of error due to unknown snow cover and emergence through marine waters, I will present two models to constrain production rate variability. Estimates for snow cover correction were calculated using a suite of samples collected along an altitudinal gradient on a lava flow of known age. The model for emergence for sea level uses a simple equation for isostatic uplift and limited data on relative sea-level history.

DATING METHODS

Radiocarbon Ages

Detrital wood was collected from ice-proximal deposits exposed in a borrow pit near the Porteau moraine (Fig. 3). The samples were collected from a silty layer that contains casts of barnacle-covered cobbles. This layer is part of marine delta foreset beds that unconformably overlie ice-proximal sediments associated with the Porteau morainal complex (Fig. 4). Radiocarbon ages were obtained from the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory (LLNL), California. Radiocarbon dates were calibrated to calendar years using the program CALIB 4.1 (Stuiver and Reimer, 1993) and calibration data from Stuiver *et. al.* (1998). Radiocarbon dating from this study was tied to chronologies published in other regional studies (Brooks and Friele, 1992; Kovanen and Easterbrook, in press; Clague *et. al.,* 1997).

Cosmogenic-chlorine Ages

Abraded bedrock surfaces both up- and down-glacier from the Porteau moraine were sampled for ^{36}Cl analysis (Fig. 3). Additional samples were collected from boulders > 1 m in diameter up-valley from the moraine and from the surface of the Ring Creek lava flow (Fig. 3). Three or more samples were chipped from the top surface of exposed bedrock knobs and boulders at each site using an airless jackhammer. When possible, < 1 cm of the rock was removed during sampling to minimize scaling for depth-dependent

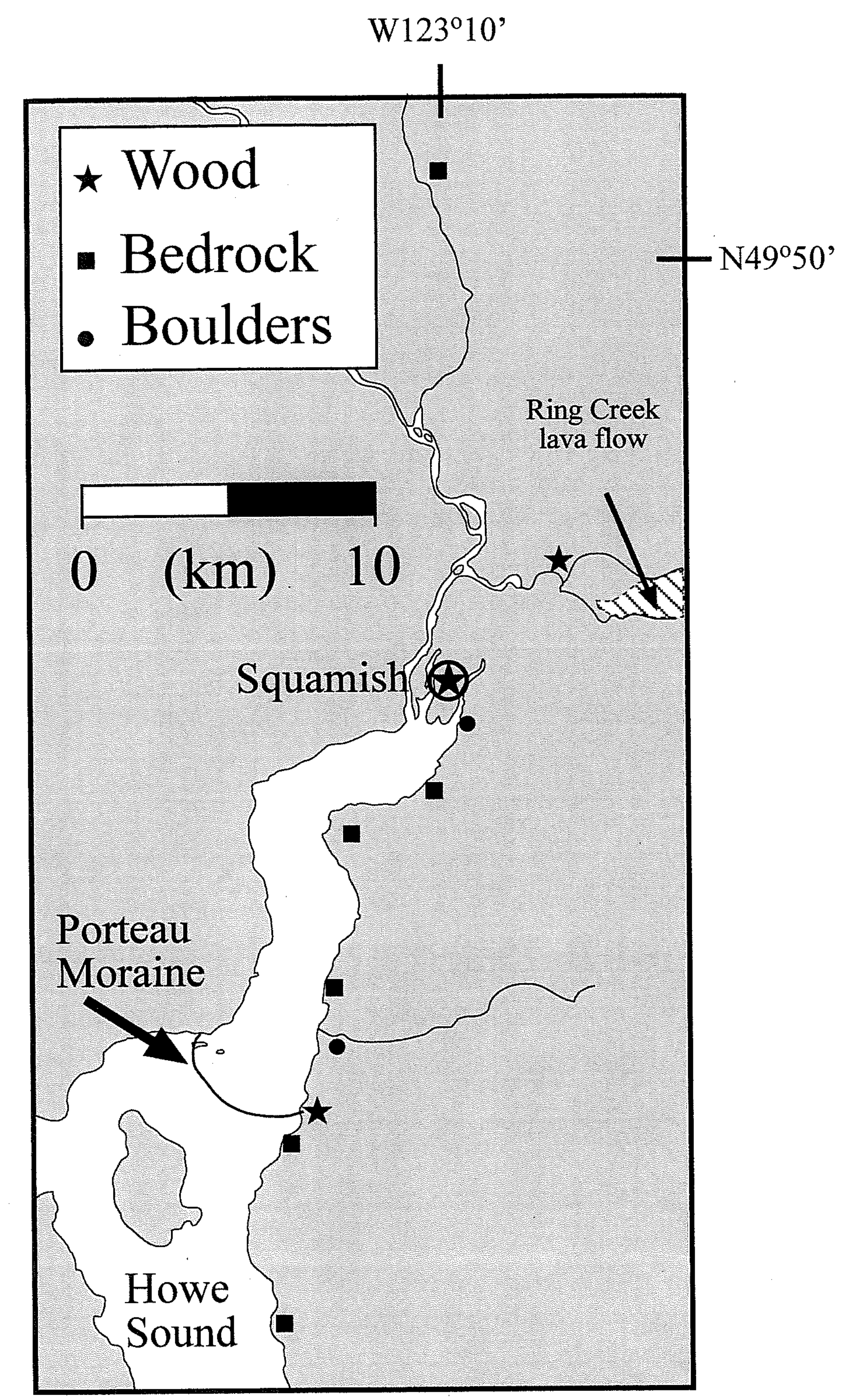

Figure 3. Sampling localities for ^{36}Cl and ^{14}C dating used in this study. The wood sample northwest of Squamish was collected by Brooks and Friele (1992).

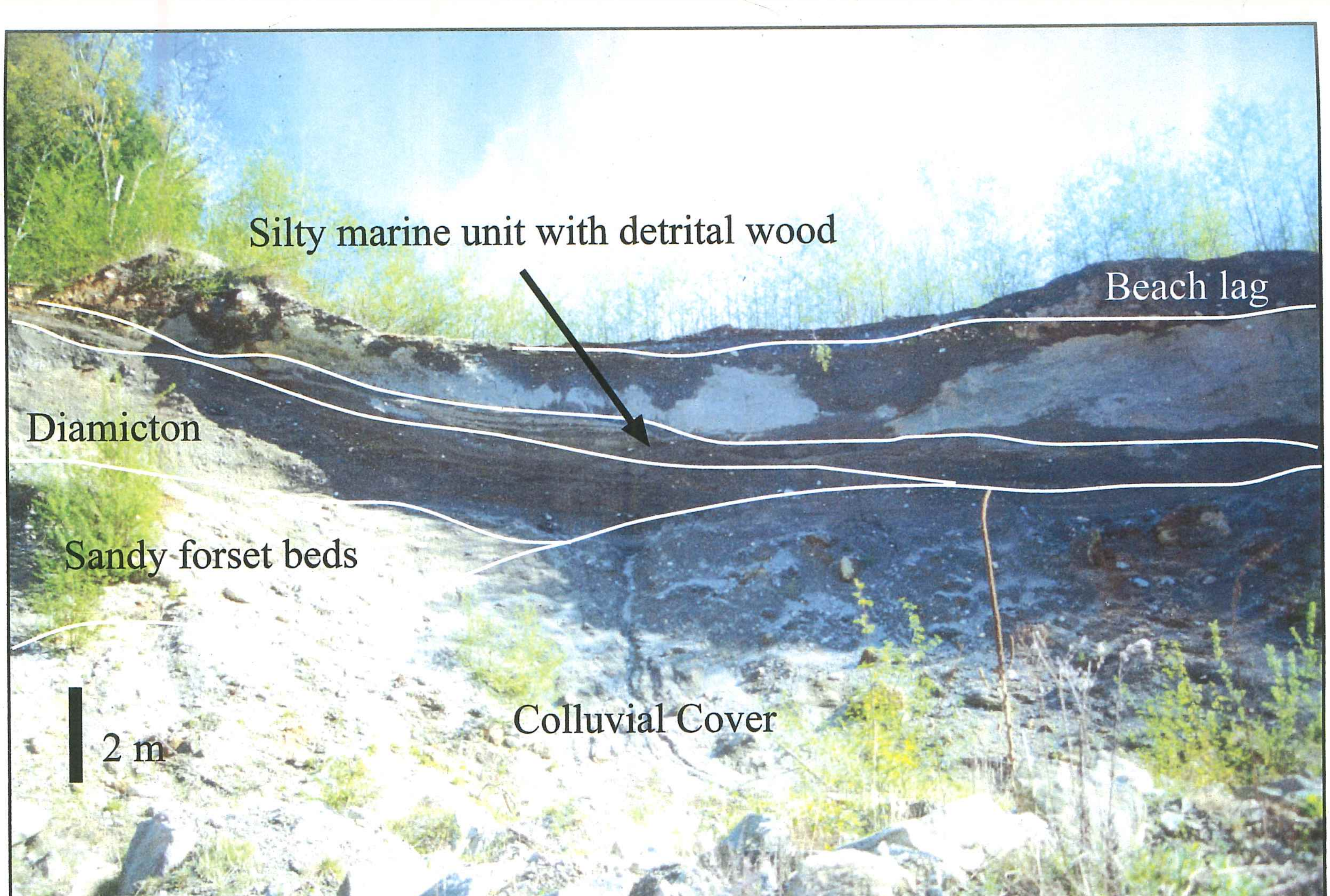

Figure 4. Photograph of quarry at Porteau Cove. Wood samples used for radiocarbon dating in this study were collected from the silty unit. An unconformity lies between the diamicton and overlying marine foreset beds (silty unit).

complexities of ^{36}Cl production. Samples were only collected from relatively flat surfaces having dip angles of < 10°. Topographic shielding was recorded at each sample locality and generally required < 3% correction. Glacial abrasion features, such as striations and grooves, were observed on all sampled bedrock surfaces, indicating that postglacial weathering has been minor at the sample sites. It has been shown at Mt. Erie, on Fidalgo Island, that glacial abrasion under the Cordilleran Ice Sheet was not great enough to remove inherited ^{36}Cl (Briner and Swanson, 1998). However, ice was thicker and persisted longer over Howe Sound than over Mt. Erie. Therefore abrasion probably was great enough to remove > 3 m of bedrock surface and is unlikely to contain inherited ^{36}Cl.

Major-element composition of rock samples was determined by standard X-ray fluorescence (XRF) spectrometry having an analytical uncertainty of < 2% and a detection limit of 0.01%. Analysis for boron and gadolinium were determined by prompt gamma emission spectrometry, with an analytical uncertainty of < 2% and a detection limit of 0.5 ppm. Uranium and thorium contents were determined by neutron activation with an analytical uncertainty of < 2% and a detection limit of 0.5 ppm. XRAL Laboratories in Don Mills, Ontario, Canada, performed the major and trace elemental analyses. Total chlorine content was determined by accaralerated mass spectrometry (AMS) using a known ^{37}Cl spike and combination ion-selective electrode using modified procedures discussed by Aruscavage and Campbell (1983). Ion-selective electrode analyses were performed in the Quaternary Isotope Laboratory, University of Washington.

To extract Cl from silicate rock in a form suitable for AMS measurement, a wet chemical technique was used, modified from Zreda *et. al.* (1991) and discussed by Swanson and Caffee (2001). For those samples that were enriched with ^{37}Cl relative to ^{35}Cl, the spike was added prior to dissolving the sample. To minimize any error introduced by the isotope dilution technique, the concentration of chloride spike added was chosen to achieve a $^{37}Cl/^{35}Cl$ value of 1. Samples were analyzed for ^{36}Cl by AMS on a tandem Van de Graaf accelerator at the Center for Accelerated Mass Spectrometry (CAMS). Calculations were made using production rates of Swanson and Caffee (2001) derived from nearby Puget Lowland. Individual ^{36}Cl ages were calculated using the computer program CHLOE [Chlorine-36 exposure (Phillips and Plummer, 1996)], which uses altitudinal and latitudinal scaling factors from Lal (1991). An error-weighted statistical method,

$$Mean\ Age = Minimum\left(\sum_{i=1}^{k}\frac{[Estimated\ Age - Sample\ Age(i)]^2}{[Sample\ Error(i)]^2}\right),$$

was used to calculate the mean exposure age for a sample location.

EFFECTS OF SNOW COVER AND EMERGENCE ON ^{36}CL AGES

Many factors affect the concentration of cosmogenic nuclides in rock samples. The relative importance of these factors varies depending on the geomorphic setting and length of exposure. In Howe Sound, the three most important factors are seasonal snow cover, isostatic recovery, and eustatic sea-level rise. The latter two can be treated with one model that addresses issues of bedrock emerging through sea level and resulting atmospheric pressure changes related to isostatic recovery. For high-altitude sites where snow cover becomes important, a snow-cover model was generated that corrects for snowfall over the past 12,200 years up to 720 m altitude.

Snow Cover

Snow cover can be a large source of calculated age uncertainty, especially in maritime climates that may generate significant depths of dense snow. Often modern snow depths are used to correct the cosmic ray flux. However, these are not always representative of snow cover for the history of the sample and can over or underestimate the correction factor. At high elevations, such as at Paradise Park (~1500 m) on Mt. Rainier where snow cover can be many meters for 6 or more months of the year, not correcting for snow can result in calculated ages that underestimate the true age by 2000 to 3000 years (Apostle, 2000). Because of typically warm and wet conditions, maritime climate can have a strong control on snow depth along coastal mountains. As seen in Figures 5a and 5b, the altitudinal gradient of snowfall has a steep threshold on the windward side of coastal mountains, in contrast to a gradual increase with elevation on the lee side. In addition, snow in this region is denser along the upwind side of the mountains (Ebbesmeyer and Strickland, 1995). Because equivalent water thickness controls cosmic ray attenuation through snow, attenuation of the cosmic ray flux will be greater on the coastal side of the mountains for corresponding elevations. Mathewes and Heusser (1981) using pollen records, showed that the climate of the past 12,000 years was generally colder and wetter then the modern climate (Fig. 6). Common practice of researchers using cosmogenic isotopes to date alpine moraines is to use modern snowfall data as a proxy for the past, but this would result in underestimating the correction factor.

To correct for effects of Holocene snow depth, I collected samples from different altitudes along a transect up the Ring Creek lava flow (Fig. 7). The age of the lava flow is bracketed by radiocarbon ages of 10,600 and 12,700 cal yr BP (Brooks and Friele, 1994). The maximum age was obtained from an in-situ stump that is contained within a unit that is stratigraphically below the lava flow. The minimum age was obtained from charcoal collected from alluvial fan sediments derived from the lava flow. Geomorphic and stratigraphic evidence indicate that the older age most closely limits the age of the flow (Brooks and Friele, 1994). For each sample site, the snow-scaling factor was

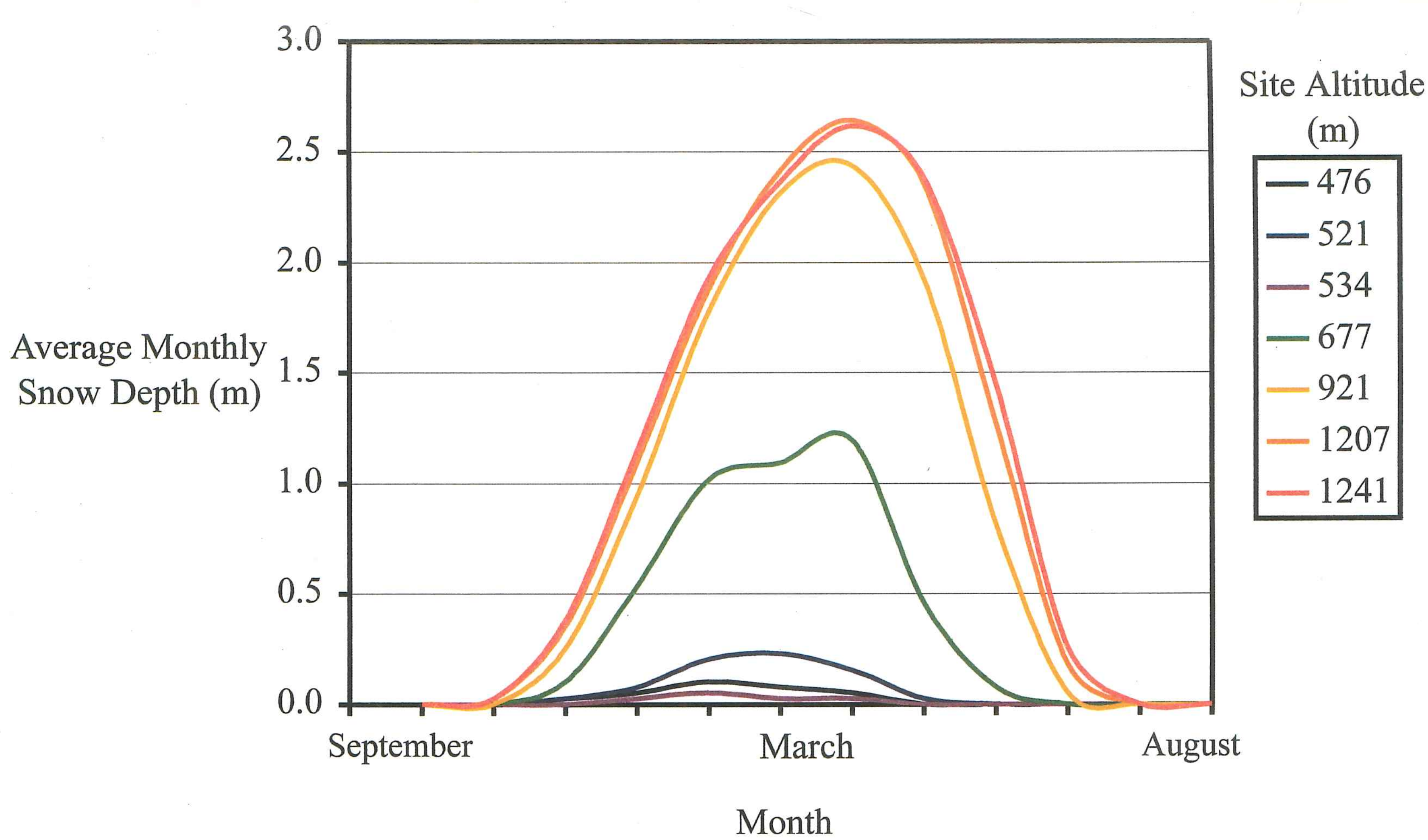

Figure 5a. Snowfall data from the western Cascade Range, Washington. Data at individual sites were collected over various time spans through the later part of the 20th century. Data obtained from Western Regional Climate Center.

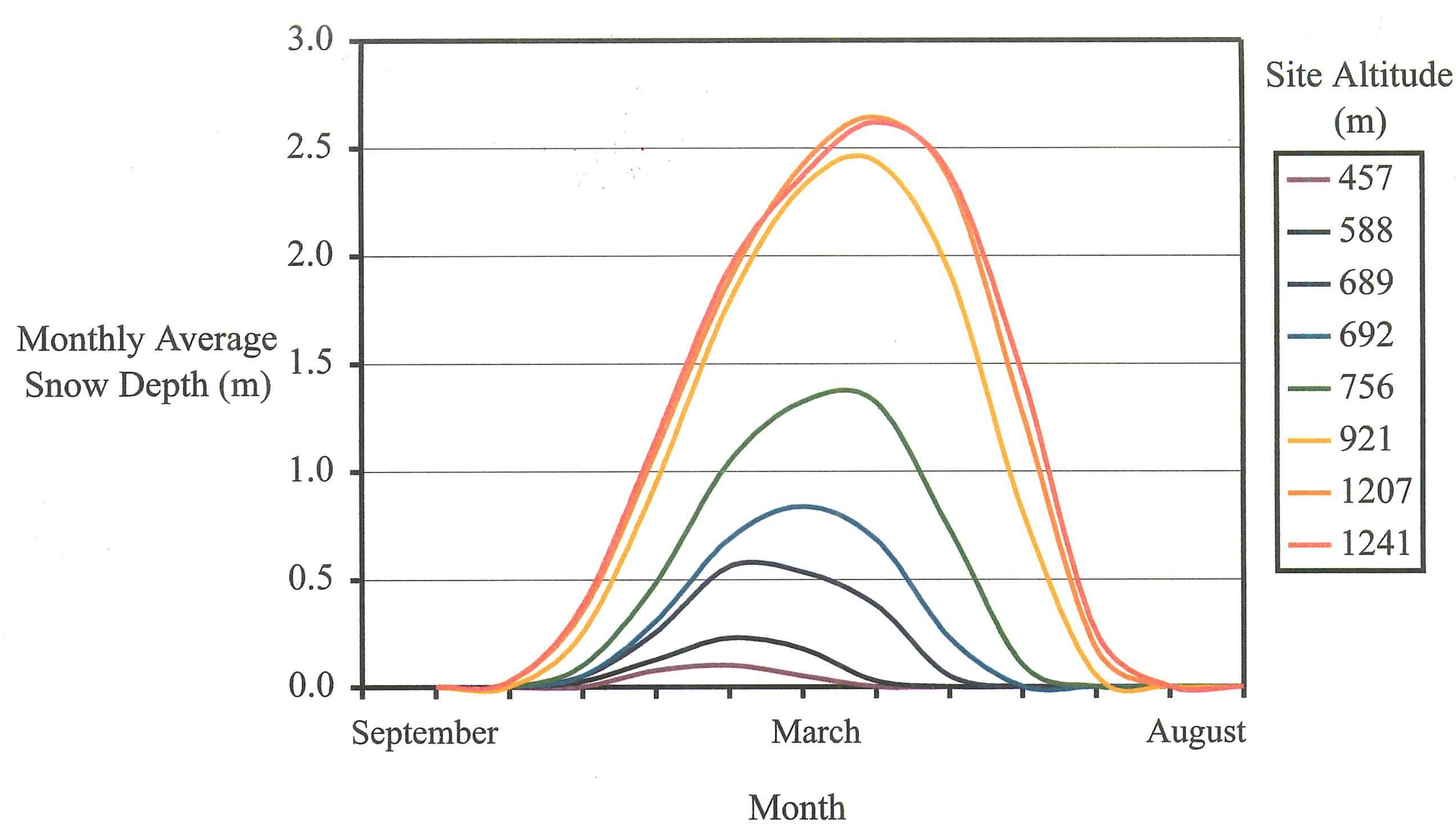

Figure 5b. Snowfall data from the eastern Cascade Range, Washington. Data at individual sites were collected over various time spans through the later part of the 20th century. Data obtained from Western Regional Climate Center.

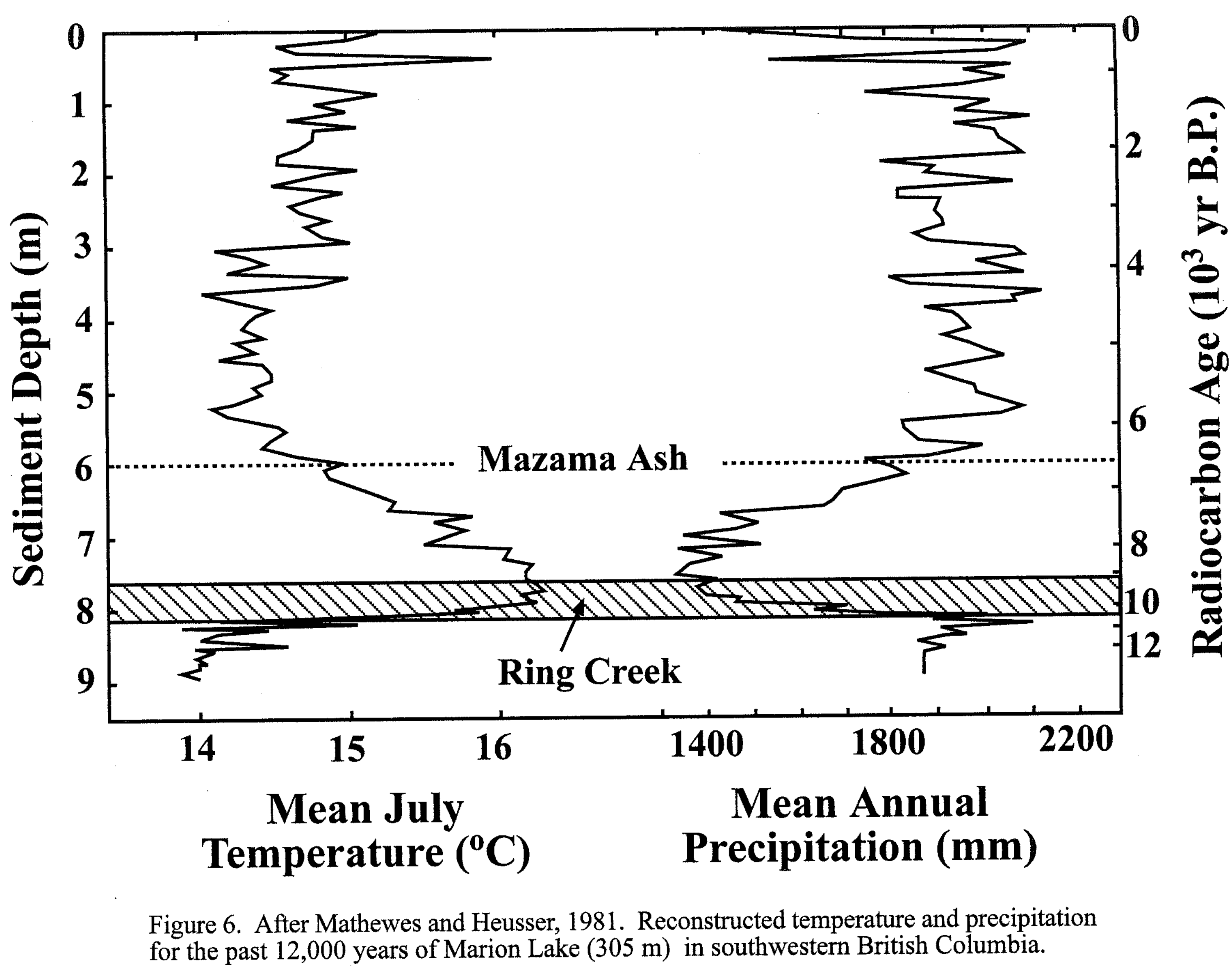

Figure 6. After Mathewes and Heusser, 1981. Reconstructed temperature and precipitation for the past 12,000 years of Marion Lake (305 m) in southwestern British Columbia.

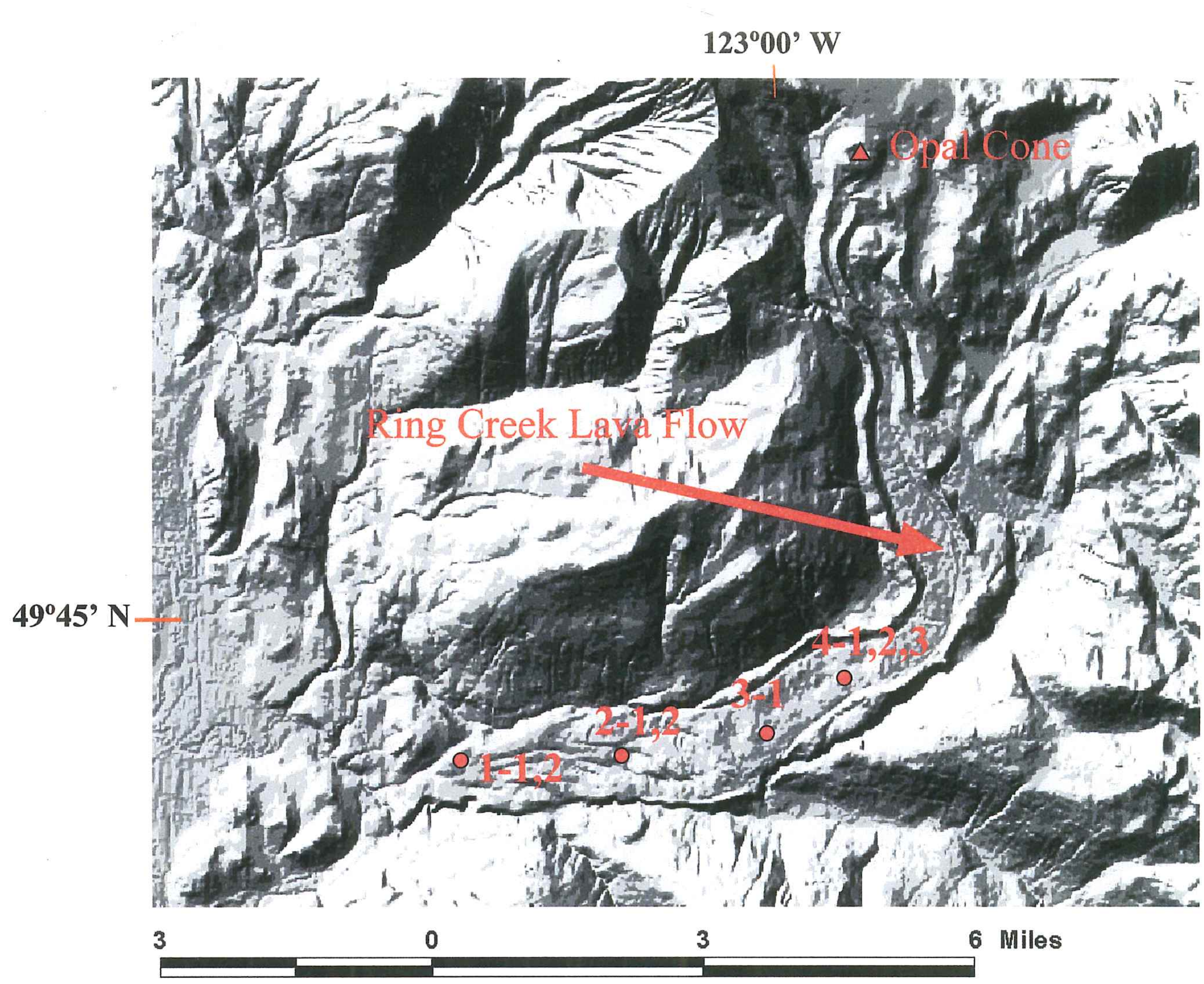

Figure 7. Shaded relief map of Ring Creek lava flow and locations of boulder samples taken for ^{36}Cl age dating. Elevation increases from sample site 1 to Opal Cone (5100 ft).

calculated to compensate for differences in ages due to reduction in total production rate (Appendix A). Differences in sample age and age of the lava flow were assumed to be due only to snow cover. Snow cover over the Ring Creek 1 (300 m) site is assumed to have been negligible. An age of 12,200 ^{36}Cl yr BP is obtained for the lava flow. Individual scaling factors were averaged for each sample site (Appendix A). Figure 8 shows snow-scaling factor change relative to elevation and also shows the anomalous increase between sites 3 and 4. If the age difference were the result of error in the altitudinal scaling factor, we would expect to see a decrease in age from sites 1 to 4. The data indicate that this anomaly is similar to what is observed today in the western Cascades (Fig. 5a). However, the elevation of this anomaly is a composite value and represents the average elevation of the anomaly for the past 12,000 years. These scaling factors provide a broad estimate on the average snow depths in Howe Sound during the Holocene. From these data, it appears that scaling effects due to snow cover are not an important part of the geologic uncertainty associated with the ^{36}Cl dates below an altitude of 600 m. With the exception of Howe 5, all the sample sites within Howe Sound lie below 300 m, where snow cover scaling factors is < 1%.

Emerging Bedrock

Isostatic recovery and rising sea level present two problems in correcting calculated ages. As a result of the overlying ice burden, bedrock in Howe Sound was isostatically depressed during the last glaciation. As the ice sheet began to retreat, isostatic recovery

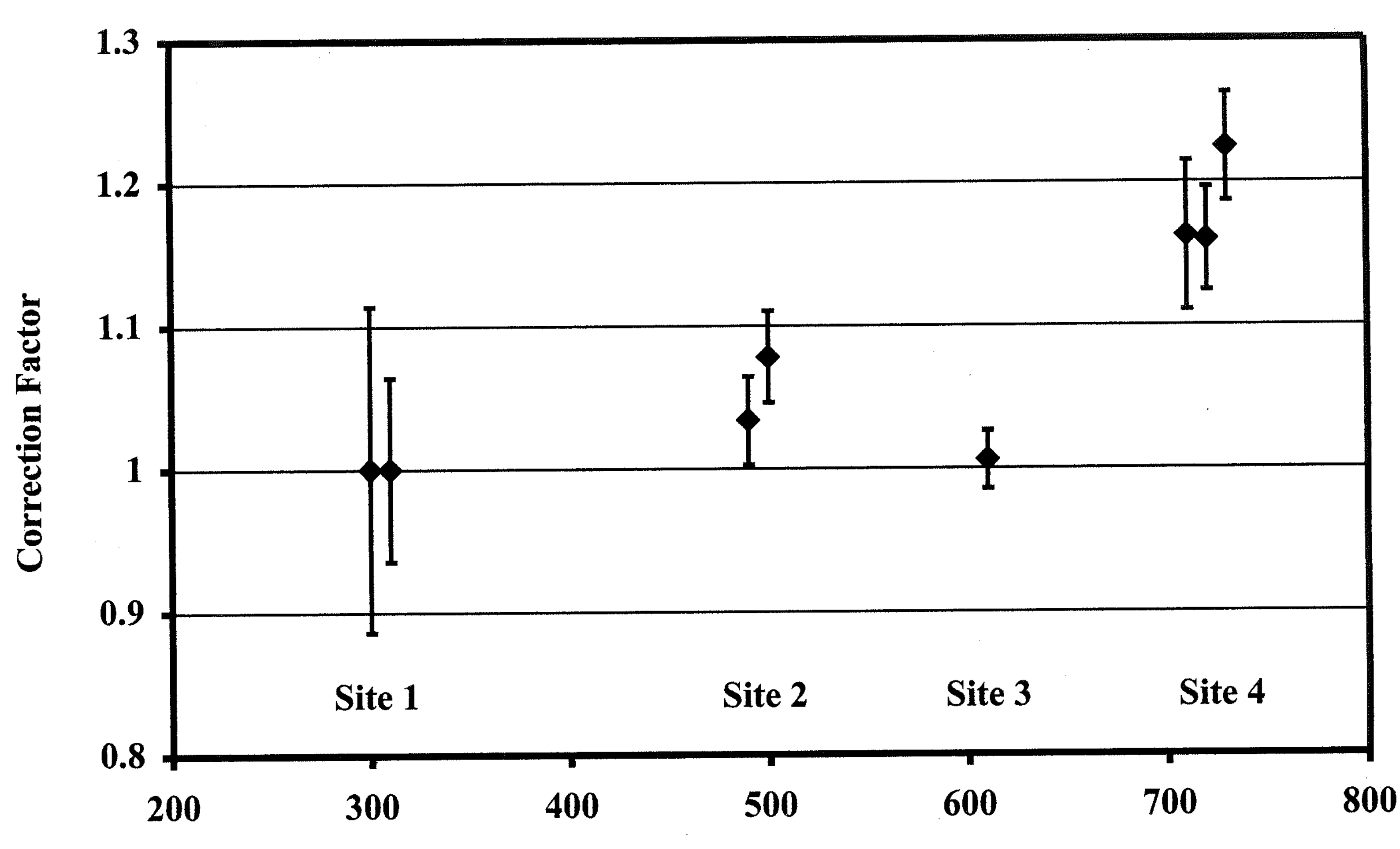

Figure 8. The snow scaling correction factor calculated for samples collected from Ring Creek lava flow increase with elevation. Sample locations increase with elevation with Ring Creek 1 at the lowest elevation and Ring Creek 4 at the highest elevation. An abrupt decrease in factor snow scaling occurs between sites 3 and 4.

commenced. During initial deglaciation relative sea level in lower Howe Sound was > 200 m (Clague, 1989) and global sea level was rising from its low of 120 m at the glacial maximum (Fairbanks, 1989). Friele and Clague (in press) determined the marine limit to be < 100 m for upper Howe Sound. Consequently, all bedrock knobs below an altitude of 100 m spent some time since deglaciation below relative sea level. Because it takes as little as 10 m of marine water to block 95% of the cosmic ray flux, it is important to model emergence of isostatically recovering bedrock through a eustatically rising sea level. In addition, bedrock surfaces above and below the marine limit continued to rise until *ca.* 7000 yr ago, causing the surface air pressure to change.

I have used a simple model based on isostatic compensation equation from Turcotte and Schubert (1982), $w = w_m e^{-t/\tau_r}$, and the eustatic sea-level curve from Fairbanks (1989) (Fig. 9). For a given site, w is remaining isostatic depression, w_m is the initial isostatic depression, t is time since isostatic recovery began, and τ_r is the characteristic time for the exponential relaxation of initial displacement. The characteristic time of relaxation (τ_r) and initial displacement (w_m) were solved empirically using relative sea-level data of Friele and Clague (in press). This model treats ice overburden at each site as a point load that was applied, reached equilibrium, and then was removed all at once. Although these assumptions are important, the associated effects are negligible and do not affect interpretation of the data.

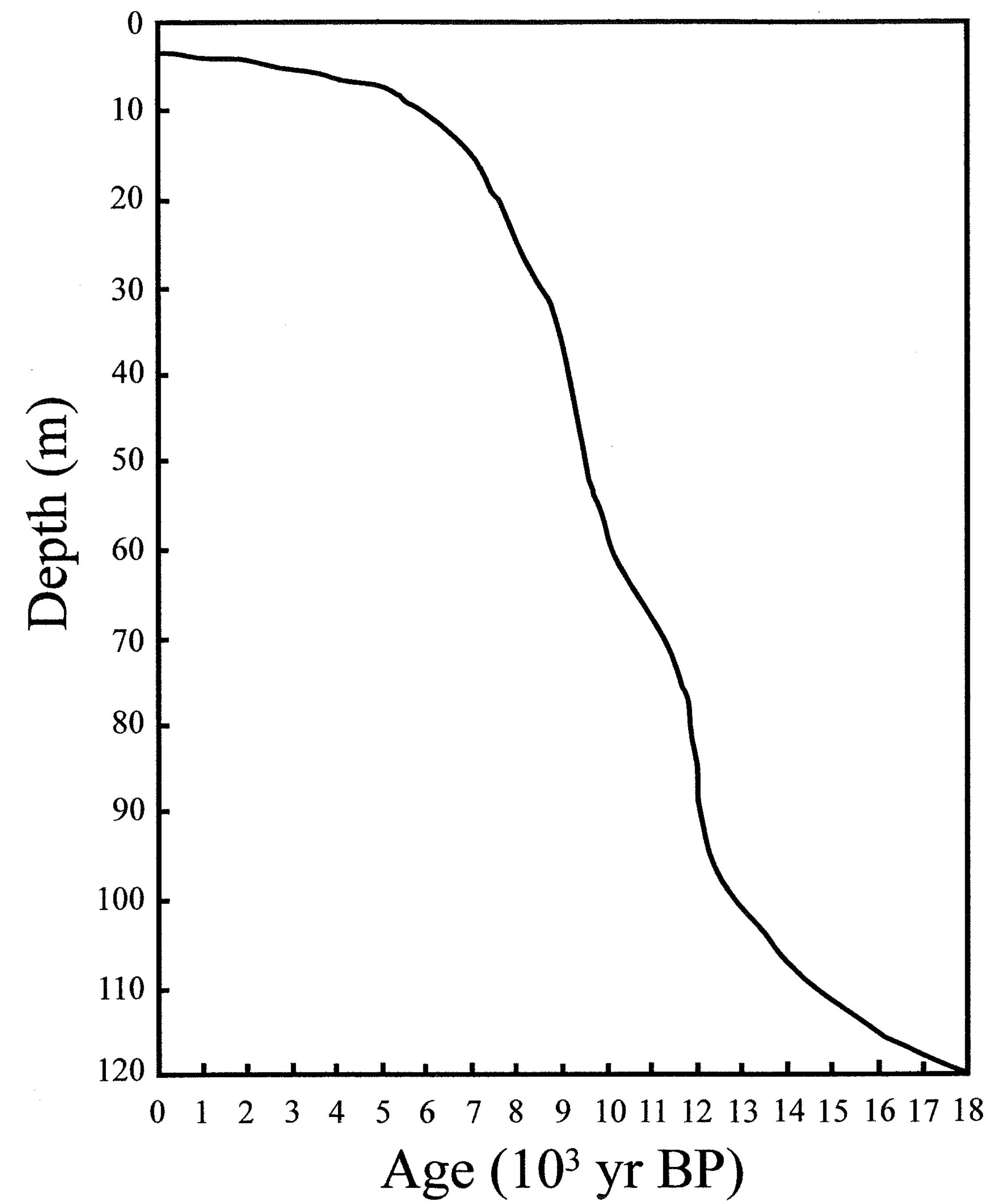

Figure 9. Eustatic sea level curve for the past 18,000 years (Fairbanks, 1989). Curve is generated from radiocarbon-dated coral from Barbados. Radiocarbon dates were corrected for local reservoir effect but were not calibrated to sidereal years.

For isostatic compensation, the difference between the model age and sample age is less then the sample uncertainty. Because initial isostatic uplift is very rapid, calculated ages for sample sites represent the emergence age for that bedrock surface. These surfaces are still polished and rounded, and indicate that emergence was rapid. Coastal erosion most likely has removed any possible sediment cover. Alternatively, it is possible that any bedrock surface experienced an extended period in the intertidal zone. This could result when the rate of isostatic uplift matches the rate of eustatic rise in sea level. Because the initial rate of isostatic recovery was much greater than the rate of rising sea level a stable coastline usually occurs some time after initial ice retreat. However, in southwestern British Columbia this occurred *ca.* 7000 yr ago. Raised marine deltas and other geomorphic evidence indicate stability of rising sea level relative to isostatic uplift.

RESULTS

Bathymetry cleary shows a morainal shoal near Porteau Cove that trends across the fjord through the Defense Islands. Bedrock surfaces are well exposed along the fjord margins and these abraded surfaces were sampled both up- and down-fjord for ^{36}Cl dating (Fig. 10). Valley walls are very steep and preserve little or no evidence of lateral moraines. Therefore, boulder samples were collected near the Porteau moraine and from a terrace south of Squamish (Fig. 10).

At Porteau Cove, two radiocarbon dates (2σ error) for wood collected from sediment overlying ice-proximal deposits are 10,120 ± 290 and 9,830 ± 50 ^{14}C yr BP and have mean calibrated ages of 12,880 (11,690) 10,750 and 11,300 (11,200), 11,170 yr BP. The ^{36}Cl ages of glacially eroded bedrock surfaces sampled down-fjord from the Porteau moraine (*i.e.,* Howe 3 and Howe 4) have mean ages of 12,400 ± 500 and 13,600 ± 600 ^{36}Cl yr BP, respectively (Fig. 11). The^{36}Cl ages of glacially eroded bedrock surfaces sample up-fjord from the Porteau moraine (*i.e.,* Howe 1, Howe 2, and Howe 6) have mean ages of 10,600 ± 600, 9,000 ± 500, and 10,000 ± 900 ^{36}Cl yr BP, respectively (Fig. 11). The ^{36}Cl ages of glacially eroded bedrock surfaces sampled 34 km up-fjord from the Porteau moraine and outside the fjord limit (*i.e.,* Howe 5) have a mean age of 9,100 ± 600 ^{36}Cl yr BP (Fig. 11). The ^{36}Cl of boulders sampled near Furry Creek (*i.e.,* Furry Creek 1-1 and 1-4) yield maximum and minimum ages for the sample site of 15,700 ±

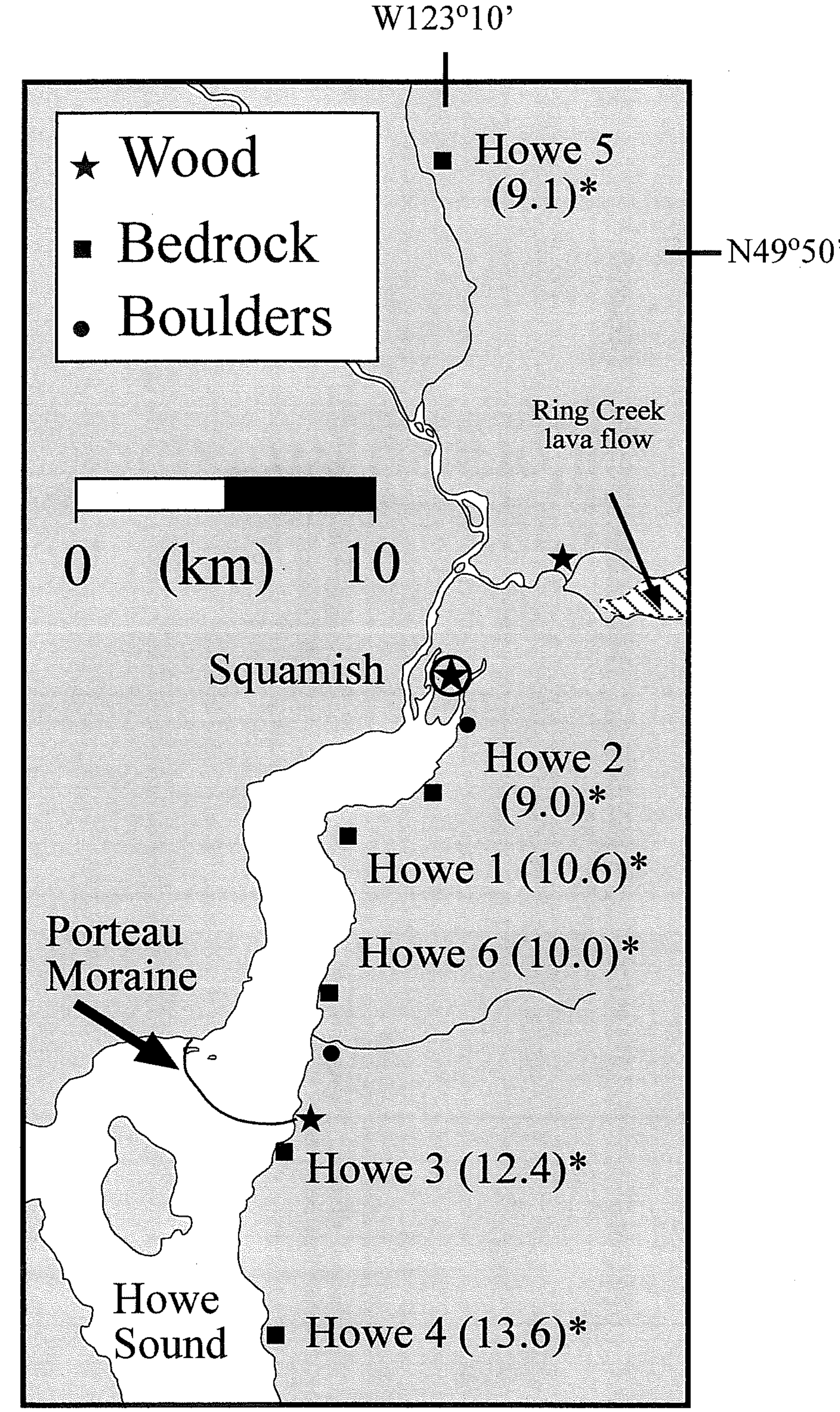

Figure 10. Mean ages of bedrock surfaces in Howe Sound. Ages given in 10^3 ^{36}Cl yr BP.

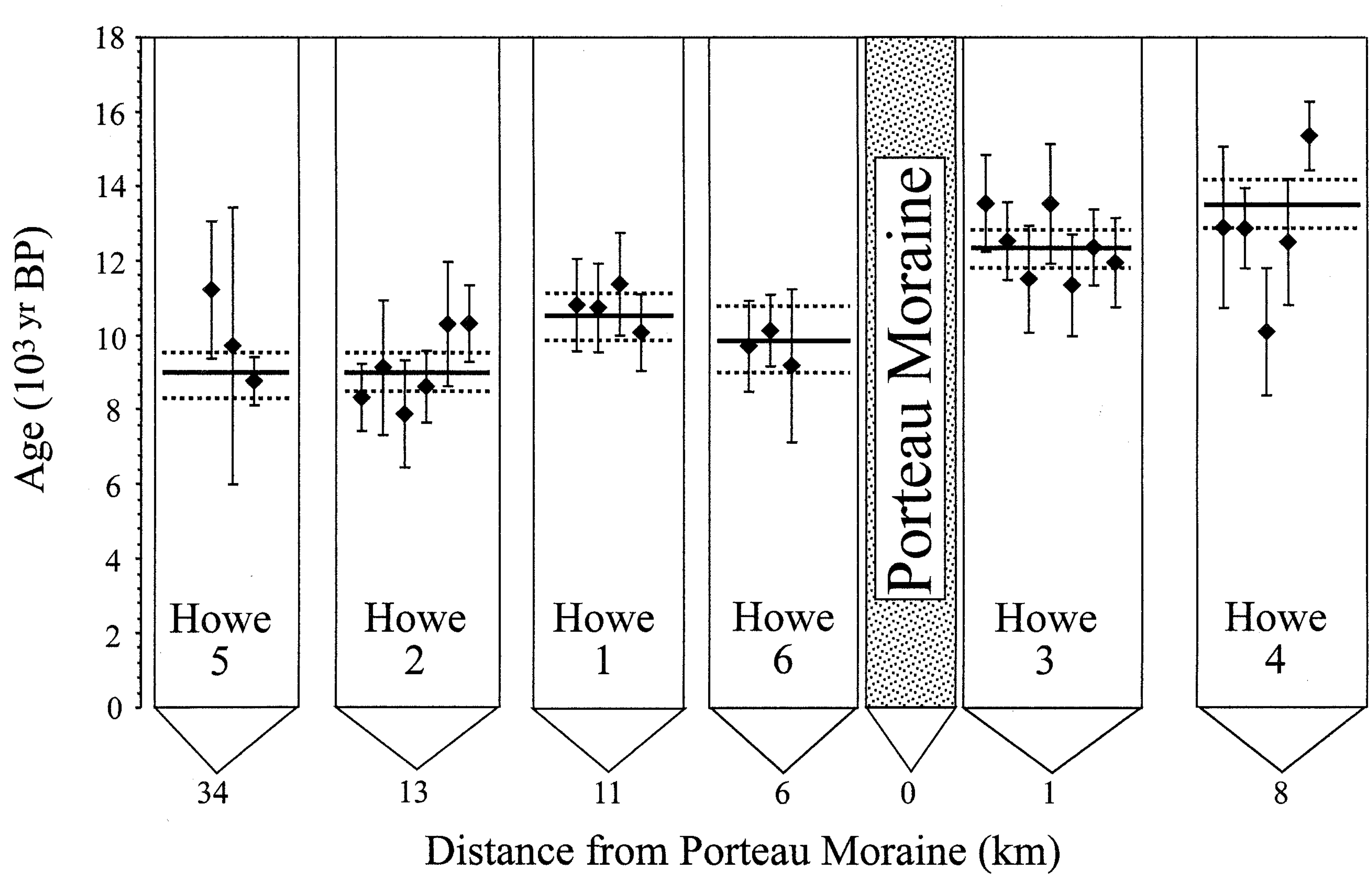

Figure 11. Calculated bedrock ages up- and down-valley from Porteau moraine. Ages given in 10^3 ^{36}Cl yr BP. Brackets indicated 1 σ error for samples. Solid lines indicate error-weighted mean and dashed lines are 1 σ error.

3,000 and 5,100 ± 4,300 ^{36}Cl yr BP. Chlorine-36 ages of boulders sampled south of Squamish (*i.e.,* Squam 1-1) provide a maximum age for the sample site of 13,000 ± 1,100 ^{36}Cl yr BP. Appendix B contains a complete list of ages and corresponding ages for various erosion rates. Appendix C, D, and E contain the complete list of site information, major element, and trace element data for each sample.

DISCUSSION

The ^{36}Cl exposure ages calculated for Howe Sound represent minimum limiting ages for deglaciation of the sampled bedrock surfaces. Chlorine-36 ages determined from bedrock surfaces down-fjord from the Porteau moraine (sample localities Howe 3 and Howe 4) represent minimum ages for deglaciation of the Cordilleran Ice Sheet in lower Howe Sound and a maximum age for deposition of the Porteau moraine. Chlorine-36 ages determined from bedrock surfaces upvalley from the Porteau moraine (sample localities Howe 1, 2, and 6) represent minimum ages for retreat of the Howe Sound lobe of the ice sheet from its limit at Porteau Cove. The ^{36}Cl ages from the sample locality Howe 2 (30 m altitude) likely represent an emergence age, the result of postglacial isostatic recovery. The unusually young mean age of Howe 2 may be due to additional complexities associated with a second readvance or stillstand terminating near the town of Squamish (Friele and Clague, in press). The age from Howe 5 (*ca.* 34 km upvalley from the Porteau moraine) is a minimum age for deglaciation of the Cheakamus River. The presence of kettle-and-kame topography suggests that this locality was covered with stagnant ice, which likely delayed exposure of bedrock surfaces. Porter and Carson (1971) have documented significant age differences between the timing of initial deglaciation and final melting of residual stagnant ice in the terminal zone of the Puget lobe of the ice sheet in northwestern Washington.

Brooks and Friele (1992) obtained a calibrated radiocarbon date of 12,960 (12,730) 12,350 yr BP from wood in a delta topset bed northwest of Squamish, near the confluence of Mamquam River and Ring Creek. The delta reaches 100 m altitude and is interpreted as having formed in an ice-marginal lake. It lies under a meter of diamicton inferred to be till (Friele and Clague, in press).

The lack of regional stratigraphic evidence leads to two possible hypothesis about the deposition of the delta:

Hypothesis A. The delta was deposited in an ice-marginal lake when the ice sheet retreated from the Porteau Cove to a position near Squamish. Because ice would have overrun the site of this delta when the glacier terminated at the Porteau moraine and there is no evidence of such occurring, this date represents a minimum age for the Porteau moraine. Thus, we can infer that all sites, except Howe 5 and possibly Howe 2, were ice-free by 12,700 cal yr BP consistent with our argument that the calculated bedrock exposure ages are minimum ages for deglaciation. The delta most likely formed during the latest readvance of ice into Howe Sound, *ca.* 12,700 cal yr BP, to a limit near Squamish. In addition, the terrace south of Squamish at 60 m altitude likely is an ice-marginal feature. The terrace probably resulted from drainage from the ice-marginal lake to the northwest of Squamish or from fluvial deposition near the glacier terminus.

Hypothesis B. The delta was deposited prior to the ice advance to Porteau Cove. At the Issaquah creek delta in the Puget Lowland, ice cover was *ca.* 1000 m but resulted in only a few meters of deformation (Porter and Swanson, 1998). Although the only deformation found is within the forset beds, deformed sediments in the topset beds may have been eroded away during a readvance. Thus, we can infer that sites Howe 3 and Howe 4 were ice-free by 12,700 cal yr BP and this age represents a maximum for the presence of ice at Porteau Cove.

Hypothesis B is the simplest explanation of the data and the best available explanation of the timing of deglaciation of Howe Sound. In addition, the absolute minimum age for deglaciation of Howe Sound is based on ^{36}Cl ages from the Howe 5 locality. The Squamish river valley was ice-free as far as the Cheakamus River valley by 9,300 ^{36}Cl yr BP and probably much earlier, because these ages represent delayed exposure of bedrock from beneath stagnant ice.

Most bedrock sample localities have been uplifted isostatically since deglaciation began. Two geologic factors need to be addressed in order to interpret the calculated bedrock exposure ages: (a) the age represents the accumulated history of varying production rates due to an increase in altitude over time (possibly most significant at sites Howe 2, 3, 4, and 6); and (b) in addition to increasing altitude, the age represents an emergence age related to falling relative sea level (possibly sites Howe 2, 3, and 4). Bedrock exposure ages were not adjusted for sample sites affected by either history; therefore, the calculated age is a minimum for deglaciation of those surfaces. Estimated adjustment for uplift increases the age of Howe 6 by *ca.* 3 %. This estimate was made using the model presented previously. In addition to the geologic uncertainty associated with the sampling sites there is an uncertainty incorporated into the calculated ages from varying magnetic field strength and polar wander. The geographic location of the samples and the short exposure history cause them to be sensitive to polar wander. Correcting for these two components can increase the age by 300 to 400 years (J. Stone, personal communication, 2000). Because both sources of error are small and well within the margin of error, no corrections were made to the calculated ages.

CONCLUSIONS

Broad timing constraints, lack of stratigraphic evidence of readvance, and location of Porteau Cove as a natural pinning point for retreating or advancing ice prevent determination of the cause of the late-glacial ice stand that deposited the Porteau moraine. On the basis of available ^{14}C and ^{36}Cl ages for hypothesis A and B, the late-glacial advance or stillstand of the Cordilleran Ice Sheet in Howe Sound was broadly contemporaneous with the readvance(s) of ice in the central Fraser Lowland (Clague *et al.,* 1997) and the readvance(s) of in northern Washington (Kovanen and Easterbrook, in press) (Fig. 12). The general agreement of the limiting ages for readvance or halt of the ice-sheet margin in two different fjord systems suggests that these events may represent a regional climatic event. Even though the Porteau moraine falls within the European Younger Dryas interval (12,700-11,400 cal yr BP), it need not be related to North Atlantic cooling. As for the second advance or stillstand near Squamish, lack of geologic evidence prevents any conclusions other than its maximum limiting age is 10,600 yr BP. The results of this study do not rule out either cause in support of the concept of the simultaneous grounding and readvance of the two ice margins. One promising approach to solving this problem would be to obtain dates for a third valley system in which glaciers were grounded on bedrock during this late-glacial interval.

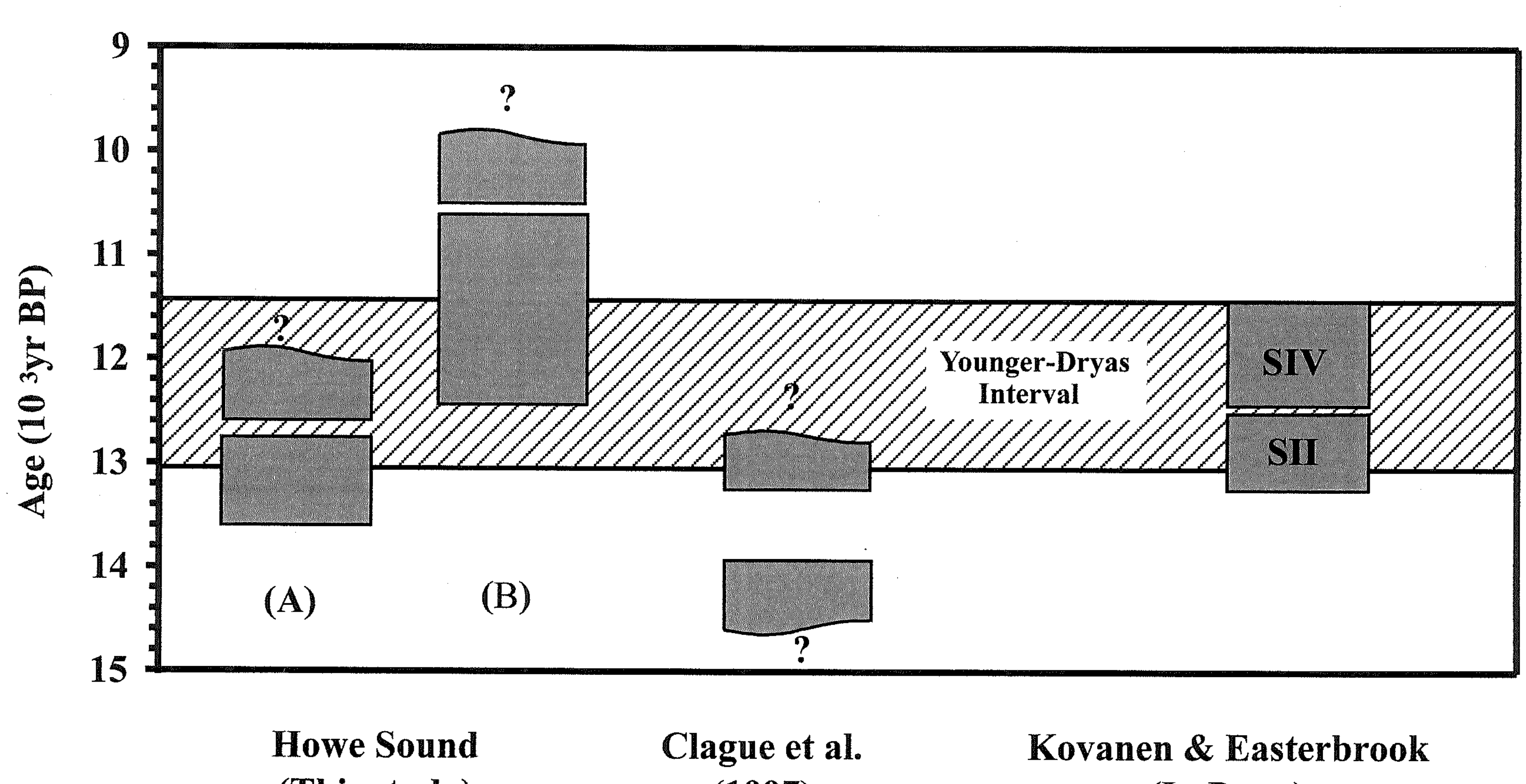

Figure 12. Comparison of results from this study, Clague *et. al.*, (1997), and Kovanen and Easterbrook (1996). Ages from this study are given in 10^3 ^{36}Cl yr BP. Ages from the other studies are given in 10^3 calibrated radiocarbon years BP. Question marks indicate no available limiting ages.

REFERENCES CITED

Apostle, P. F., 2000, Influence of a Thick Annual Snowpack on 36Cl Surface-Exposure Ages on Mount Rainier, Washington: EOS Transactions AGU Fall Supplement, v. 48, p. 81. (Check Refence)

Armstrong, J. E., Crandell, D. R., Easterbrook, D. J., and Noble, J. B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geological Society of America Bullein, v. 76, p. 321-330.

Aruscavage, P. J. and Campbell, E. Y., 1983, An ion-selective electrode method for determination of chlorine in geological materials: Talanta, v. 28, 745-749.

Briner, J. P. and Swanson, T. W., 1998, Using inherited cosmogenic ^{36}Cl to constrain glacial erosion rates of the Cordilleran ice sheet: Geology, v. 26, p. 3-6.

Brooks, G. R. and Friele, P. A., 1992, Bracketing ages for the formation of the Ring Creek lava flow, Mount Garibaldi volcanic field, southwestern British Columbia: Canadian Journal of Earth Sciences, v. 29, p. 2425-2428.

Clague, J. J., 1989, Quaternary sea levels (Canadian Cordillera); Chapter 1 of Quaternary Geology of Canada and Greenland, R. J. Fulton (ed.): Geological Society of America, The Geology of North America, v. K-1, p. 43-47.

Clague, J. J., Mathewes, R. W., Guilbault, J.-P., Hutchinson, I., and Rickets, B.D., 1997, Pre-Younger Dryas resurgence of the southwestern margin of the Cordilleran ice Sheet, British Columbia, Canada: Boreas, v. 26, p. 261-277.

Ebbesmeyer, C. C. and Strickland, R. M., 1995, Oyster condition and climate: evidence from Willapa Bay. Washington Sea Grant Program.

Fairbanks, R. G., 1989, A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: Nature, v. 342, p. 637-642.

Friele, P. A. and Clague, J. J., In Press, Readvance of glaciers in the British Columbia Coast Mountains at the end of the last glaciation: Quaternary International.

Kovanen, D. J. and Easterbrook, D. J., In Press, Timing and extent of Allerod and Younger Dryas age (ca. 12,500-10,000 ^{14}C yr B.P.) oscillations of the Cordilleran Ice Sheet in the Fraser Lowland, Western North America: Quaternary Research.

Lal, D., 1991, Cosmic ray labeling of erosion surfaces: In situ nuclide production rates and erosion models: Earth and Planetary Science letters, v. 104, p. 424-439.

Mathewes, R. W. and Heusser, L. E., 1981, A 12 000 year palynological record of temperature and precipitation trends in southwestern British Columbia: Canadian Journal of Botany, v. 59, p. 707-710.

Phillips, F. M. and Plummer, M. A., 1996, CHLOE: A program for interpreting *in-situ* cosmogenic nuclide data for surface exposure dating and erosion studies: Radiocarbon, v. 38, p. 98.

Porter, S. C. and Carlson J. C. III, 1971, Problems of interpreting radiocarbon dates from dead-ice terrain, with an example from the Puget Lowland of Washington: Quaternary Research, v. 1, no. 3, p. 410-414.

Porter, S. C. and Swanson, T. W., 1998, Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran Ice Sheet during the last glaciation: Quaternary Research, v. 50, no. 3, p. 205-213.

Stuiver, M. and Reimer, P. J., 1993, Extended ^{14}C database and revised CALIB radiocarbon calibration program: Radiocarbon, v. 35, p. 215-230.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., v. d. Plicht, J., and Spurk, M., 1998, INTCAL98 Radiocarbon age calibration 24,000 - 0 cal BP: Radiocarbon, v. 40, p. 1041-1083.

Swanson, T. W. and Caffee, M., 2001, Determination of ^{36}Cl production rates from the deglaciation history of Whidbey and Fidalgo islands, Washington: Quaternary Research, v. 56, p. 366-382.

Turcotte, D. L. and Schubert, G., 1982, Geodynamics Applications of continuum physics to geological problems, Wiley, New York.

Appendix A. Production Rates and Snow Correction Factors

SAMPLE	Ca	K	Production Neutron	Total	Uncorrected Age*	Correction Factor	Corrected Age*
Ring Creek 1-1	4.46	3.702	14.0686	22.2	12,229	1.00	12,229
Ring Creek 1-2	4.46	3.702	15.969	24.1	11,103	1.00	11,103
Ring Creek 2-1	4.82	4.718	25.2202	34.8	11,287	1.06	11,935
Ring Creek 2-2	4.72	4.886	21.9719	31.6	10,821	1.06	11,442
Ring Creek 3-1	5.47	4.91	4.08896	14.5	11,598	1.01	11,700
Ring Creek 4-1	6.77	6.574	29.051	42.4	10,035	1.18	11,889
Ring Creek 4-2	6.91	6.528	30.1623	43.6	10,056	1.18	11,914
Ring Creek 4-3	6.45	6.575	28.9208	41.9	9,527	1.18	11,287

* Age in ^{36}Cl yr BP

Appendix B. Calculated Ages* at Various Erosion Rates (E)

Sample	Age (E=0)	1σ	(E=0.56)	1σ	(E=1.11)	1σ
Furry Creek 1-1	16,070	2,989	15,698	2,920	15,387	2,862
Furry Creek 1-2	7,077	2,088	7,019	2,071	6,965	2,055
Furry Creek 1-3	8,935	1,501	8,786	1,476	8,653	1,454
Furry Creek 1-4	5,355	4,391	5,313	4,356	5,273	4,324
Howe 1-1	10,463	1,057	10,271	1,037	10,100	1,020
Howe 1-2	11,330	1,292	11,061	1,261	10,829	1,235
Howe 1-3A	10,386	1,496	10,171	1,465	9,980	1,437
Howe 1-3B	10,347	1,252	10,106	1,223	9,895	1,197
Howe 2-1	10,581	1,047	10,454	1,035	10,339	1,024
Howe 2-1B	10,616	1,699	10,464	1,674	10,328	1,652
Howe 2-2	8,884	977	8,766	964	8,659	952
Howe 2-3	8,053	1,442	7,992	1,431	7,935	1,420
Howe 2-4	9,325	1,818	9,243	1,802	9,168	1,788
Howe 2-5	8,570	917	8,467	906	8,373	896
Howe 3-1	12,281	1,228	11,971	1,197	11,708	1,171
Howe 3-2	12,610	1,034	12,377	1,015	12,176	998
Howe 3-3	11,656	1,387	11,367	1,353	11,120	1,323
Howe 3-4	13,778	1,626	13,536	1,597	13,330	1,573
Howe 3-4B	11,700	1,451	11,532	1,430	11,386	1,412
Howe 3-5	12,687	1,053	12,541	1,041	12,415	1,030
Howe 3-5B	13,746	1,306	13,548	1,287	13,379	1,271
Howe 4-1	15,567	934	15,349	921	15,165	910
Howe 4-1B	12,662	1,697	12,520	1,678	12,395	1,661
Howe 4-2	10,241	1,710	10,131	1,692	10,033	1,675
Howe 4-3	13,037	1,082	12,882	1,069	12,747	1,058
Howe 4-3B	12,949	2,162	12,910	2,156	12,878	2,151
Howe 5-1	8,869	647	8,835	645	8,803	643
Howe 5-2	9,829	3,715	9,786	3,699	9,747	3,684
Howe 5-3	N.D.		N.D.		N.D.	
Howe 5-4	11,369	1,853	11,298	1,842	11,233	1,831
Howe 6-1	9,320	2,060	9,267	2,048	9,218	2,037
Howe 6-2	10,313	969	10,231	962	10,156	955
Howe 6-3	9,919	1,230	9,824	1,218	9,737	1,207
Squam 1-1	13,616	1,212	13,446	1,197	13,297	1,183
Squam 1-2	9,948	1,661	9,831	1,642	9,724	1,624
Squam 1-3	N.D.		N.D.		N.D.	

N.D. indicates no data.

* Age in ^{36}Cl yr BP

SAMPLE DATA

SAMPLE	Elevation (m)	Lattitude (deg)	Longitude (deg)	Thickness (cm)	Density (g/cm^3)	$^{36}Cl/Cl$	1σ
Howe 1-1A	275	49.65	123.22	2.0	2.7	75.6	4.5
Howe 1-1B	275	49.65	123.22	2.0	2.7	86.2	5.8
Howe 1-1C	275	49.65	123.22	2.0	2.7	69.7	6.6
Howe 1-2	275	49.65	123.22	2.0	2.7	60.4	7.2
Howe 1-3A	275	49.65	123.22	2.0	2.7	82.9	9.6
Howe 1-3B	275	49.65	123.22	2.0	2.7	70.1	8.7
Howe 1-3C	275	49.65	123.22	2.0	3.0	N.D.	N.D.
Howe 1-3D	275	49.65	123.22	2.0	2.7	139.0	16.7
Howe 2-1	30	49.67	123.17	2.0	2.7	91.4	5.4
Howe 2-2	30	49.67	123.17	2.0	2.7	79.4	4.7
Howe 2-3	30	49.67	123.17	2.0	2.7	88.4	6.6
Howe 2-4	30	49.67	123.17	2.0	2.7	86.7	12.1
Howe 2-5	30	49.67	123.17	2.0	2.7	76.8	3.0
Howe 2-6	30	49.67	123.17	2.0	2.7	70.0	3.6
Howe 3-1	99	49.55	123.23	2.0	3.0	63.4	4.7
Howe 3-2	99	49.55	123.23	2.0	3.0	76.0	4.5
Howe 3-3	99	49.55	123.23	2.0	3.0	59.7	3.0
Howe 3-4	99	49.55	123.23	2.0	3.0	80.0	3.8
Howe 3-5	99	49.55	123.23	2.0	3.0	95.0	6.2
Howe 4-1	67	49.5	123.25	2.0	2.7	117.2	12.1
Howe 4-2	67	49.5	123.25	2.0	2.7	96.5	12.3
Howe 4-3	67	49.5	123.25	2.0	2.7	202.5	28.8
Howe 5-1	308	49.85	123.15	2.0	2.7	170.0	5.6
Howe 5-2	302	49.85	123.15	2.0	2.7	194.0	10.4
Howe 5-3	302	49.85	123.15	2.0	2.7	N.D.	N.D.
Howe 5-4	302	49.85	123.15	2.5	2.7	191.0	6.6
Howe 6-1	122	49.6	123.22	2.0	2.7	125.0	7.5
Howe 6-2	122	49.6	123.22	2.0	2.7	110.0	5.7
Howe 6-3	122	49.6	123.22	2.0	2.7	92.4	4.1
Squam 1-1	60	49.68	123.15	2.0	3.0	120.9	3.7
Squam 1-2	60	49.68	123.15	2.0	3.0	87.5	5.6
Squam 1-3	60	49.68	123.15	2.0	3.0	N.D.	N.D.
Ring Creek 1-1	300	49.72	123	1.0	2.8	60.5	6.87
Ring Creek 1-2	300	49.72	123	1.0	2.8	48.5	4.6
Ring Creek 2-1	491	49.72	123	1.5	2.8	57.3	1.7
Ring Creek 2-2	491	49.72	123	1.0	2.8	56.3	1.7
Ring Creek 3-1	610	49.73	122.99	1.5	2.8	162.5	3.3
Ring Creek 4-1	719	49.74	122.97	1.5	2.8	62.7	2.8
Ring Creek 4-2	719	49.74	122.97	1.0	2.8	64.0	2.0
Ring Creek 4-3	719	49.74	122.97	1.5	2.8	64.3	2.0

Note: $^{36}Cl/Cl$ data were run by CAMS at LLNL, California.
N.D. indicates no data.

Appendix D. Major Element Analysis

SAMPLE	Na_2O (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	P_2O_5 (%)	K_2O (%)	CaO (%)	TiO_2 (%)	MnO (%)	Fe_2O_3 (%)
Howe 1-1A	3.44	0.32	12.3	76.2	0.04	2.64	1.97	0.19	0.03	2.17
Howe 1-1B	3.88	0.29	13.7	73.9	0.04	2.87	2.21	0.197	0.03	2.04
Howe 1-1C	3.63	0.98	13	71.7	0.06	2.54	2.46	0.375	0.11	4.22
Howe 1-2	3.85	0.26	13.2	74.6	0.03	2.61	2.17	0.178	0.03	2.09
Howe 1-3A	3.46	0.17	12	78.1	0.02	2.4	1.9	0.153	0.03	1.8
Howe 1-3B	4.01	0.34	13.9	72.9	0.06	2.95	2.17	0.202	0.04	2.28
Howe 1-3C	2.97	2.98	19.2	54	0.19	0.19	9.55	0.693	0.12	8.3
Howe 1-3D	2.95	0.01	10.7	79.9	0.01	4.6	0.48	0.064	0.01	0.87
Howe 2-1	3.44	0.19	12.1	77	0.03	3.23	1.54	0.158	0.03	2.09
Howe 2-2	3.59	0.19	12.3	76.3	0.03	3.04	1.55	0.147	0.03	1.7
Howe 2-3	3.6	0.19	12.6	75.9	0.05	3.2	1.54	0.162	0.03	2.1
Howe 2-4	3.58	0.09	12.2	77.6	0.02	3.09	1.58	0.113	0.02	1.39
Howe 2-5	3.47	0.18	12.1	77.1	0.03	3.11	1.57	0.155	0.03	2.08
Howe 2-6	3.76	0.21	12.9	75.8	0.04	2.97	1.83	0.158	0.03	2.11
Howe 3-1	2.83	2.59	16	61.4	0.15	0.8	3.61	0.632	0.15	9.49
Howe 3-2	3.13	2.39	16.3	60.7	0.14	1.35	3.27	0.629	0.11	9.01
Howe 3-3	2.77	2.3	15.4	62.5	0.12	1.23	2.97	0.79	0.1	9.12
Howe 3-4	1.79	2.43	16	63.5	0.12	2.37	1.97	0.728	0.07	8.49
Howe 3-5	1.62	2.33	15.5	64.7	0.12	2.38	2	0.848	0.06	7.48
Howe 4-1	3.07	1.94	12.3	70	0.14	1.63	2.43	0.687	0.12	5.06
Howe 4-2	3.25	1.09	12.4	70.8	0.11	0.48	4.51	0.567	0.12	4.36
Howe 4-3	3	1.72	14.2	65.8	0.17	1.63	3.95	0.749	0.12	5.31
Howe 5-1	3.83	1.86	16.7	64.2	0.12	1.29	4.2	0.325	0.09	3.81
Howe 5-2	3.88	1.59	16.7	64.9	0.12	1.11	5.14	0.315	0.1	3.71
Howe 5-3	3.97	1.64	16.6	65.5	0.11	1.32	4.34	0.342	0.09	3.91
Howe 5-4	4.05	1.68	15.7	66.6	0.13	1.17	3.81	0.329	0.09	3.8
Howe 6-1	3.12	1.8	14.6	66.9	0.09	1.4	4.59	0.469	0.08	4.76
Howe 6-2	3.23	1.88	15.1	67.5	0.09	1.56	4.75	0.479	0.06	4.4
Howe 6-3	3.03	2.12	14.9	65.5	0.09	1.59	5.12	0.498	0.07	4.59
Squam 1-1	4.03	0.31	13.9	74	0.06	3.65	1.66	0.184	0.06	1.91
Squam 1-2	3.74	0.17	12.1	77.5	0.03	2.63	1.69	0.139	0.04	1.53
Squam 1-3	3.45	0.21	12.7	76.2	0.03	3.81	1.48	0.144	0.04	1.82
Ring Creek 1-1	4.15	2.57	16.7	63.3	0.1	1.45	5.19	0.59	0.09	5.04
Ring Creek 1-2	4.15	2.57	16.7	63.3	0.1	1.45	5.19	0.59	0.09	5.04
Ring Creek 2-1	4.11	2.81	15.6	62.8	0.13	1.59	4.82	0.599	0.09	4.98
Ring Creek 2-2	3.98	2.75	15.3	64.6	0.14	1.64	4.7	0.59	0.09	4.88
Ring Creek 3-1	4.43	2.77	16.6	62.2	0.22	1.51	4.99	0.606	0.11	5.34
Ring Creek 4-1	4.3	2.72	16.3	61.6	0.2	1.79	5.47	0.619	0.09	5.11
Ring Creek 4-2	4.26	2.74	16.5	61.8	0.2	1.76	5.53	0.614	0.09	5.28
Ring Creek 4-3	4.01	2.64	15.8	62.2	0.15	1.78	5.18	0.61	0.08	4.81

Note: Major elemental composition were run by XRAL, Canada.

N.D. indicates no data.

Appendix E. Trace Element Analysis

SAMPLE	Cl (ppm)	B (ppm)	Gd (ppm)	Sm (ppm)	U (ppm)	Th (ppm)
Howe 1-1A	149	11	2.5	2.5	1.5	4.3
Howe 1-1B	190	0.25	2	2	0.8	5.7
Howe 1-1C	268	5	4	4	2.2	13.2
Howe 1-2	224	0.25	3	3	1.4	8.7
Howe 1-3A	195	0.25	2	2	1.8	5.1
Howe 1-3B	160	0.25	2	2	2.4	9.3
Howe 1-3C	0	0.25	2	2	1.4	6.7
Howe 1-3D	66	0.25	2	2	3	15.1
Howe 2-1	114	7.5	2	2	2	6.2
Howe 2-2	114	0.25	2	2	2.9	4.9
Howe 2-3	71	7	2	2	2.6	8
Howe 2-4	76	14	2.5	2.5	2.1	5.3
Howe 2-5	105	0.25	2	2	1.9	7.7
Howe 2-6	83	0.25	3	3	1.7	7.7
Howe 3-1	123	9	2.5	2.5	1.5	3.9
Howe 3-2	97	13	5	5	1.5	5.6
Howe 3-3	161	10	4	4	1.4	7.8
Howe 3-4	115	36	3	3	2.1	8.8
Howe 3-5	95	32	4	4	2.3	9.7
Howe 4-1	51	13	3.5	3.5	0.7	1.9
Howe 4-2	47	12	4	4	2	9.8
Howe 4-3	27	13	3	3	1.3	2.7
Howe 5-1	27	3	3	3	2.5	4.1
Howe 5-2	29	0.25	2	2	2.5	3.4
Howe 5-3	22	0.25	2	2	2	2.6
Howe 5-4	24	0.25	3	3	1.8	2.1
Howe 6-1	52	5	1	1	1.9	3.1
Howe 6-2	62	5	2	2	0.5	3
Howe 6-3	80	3	3	3	0.8	3.3
Squam 1-1	92	13.5	2.5	2.5	2.6	7.3
Squam 1-2	82	7	4	4	5.8	3.2
Squam 1-3	72	13.5*	2.5*	2.5*	2.6*	7.3*
Ring Creek 1-1	261	5	1	1	1.9	5.7
Ring Creek 1-2	297	5	1	1	1.9	5.7
Ring Creek 2-1	398	9	0.5	0.5	0.8	2.4
Ring Creek 2-2	353	7	0.5	0.5	0.8	2.4
Ring Creek 3-1	60	8	2	2	0.25	1.9
Ring Creek 4-1	395	9	3	3	0.6	2.1
Ring Creek 4-2	400	8	0.5	0.5	0.6	2.1
Ring Creek 4-3	362	8	0.5	0.5	0.6	2.1

Note: Trace elemental composition were run by XRAL, Canada.
N.D. indicates no data.
*Values are estimates.