Lichenometric and radiocarbon dating of Holocene glaciation, Cordillera Blanca, Perú

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Abstract: Measurements of *Rhizocarpon* subgenus *Rhizocarpon* thalli on moraines the ages of which are constrained by six radiocarbon dates, two pre-Colombian structures, and one historically-dated flood deposit indicate that lichenometry can be used to estimate the age of stabilization of glacial deposits that date to the last c. 7 ka on the west side of the Cordillera Blanca, Perú (8°40′–9°40′S; 77°00′–77°40′W). The preliminary growth curve for subgenus *Rhizocarpon* resembles those derived for alpine areas in Alaska and Colorado, and can be subdivided into an initial, rapid phase of growth (c. 0.4 mm yr^{-1}) that lasts c. 100 years, a c. 500- to 1000-year-long phase of decelerating growth, and a period of slow linear growth (0.016 mm yr^{-1}) that commences after c. 1000 years.

Size clustering of subgenus *Rhizocarpon* thalli supports a four-fold subdivision of cirque moraines at altitudes between 4200 and 4650 m. The oldest moraines stabilized between c. 7000 and 6000 BP, and the three younger groups between c. 3350 and 1800 BP, between c. 1250 and 400 BP, and within the last 100 years. This subdivision is supported by limiting radiocarbon dates from the Cordillera Blanca and from several cordilleras in southern Perú, and indicates that the Holocene glacial chronology of the Cordillera Blanca is the most complete heretofore recognized in the tropical Andes.

Key words: Andes, climatic change, glaciation, Holocene, lichenometry, radiocarbon dates.

Introduction

Numerous attempts have been made to determine the chronology of glaciation over the last 10 000 years (hereafter 10 ka) in high-altitude and high-latitude regions. Syntheses of these studies have disagreed on the global pattern of Holocene glaciation (Benedict, 1973; Denton and Karlén, 1973a; Burrows, 1979; Grove, 1979; 1988), and this has hindered the critical assessment of theories of the causes of Holocene climatic change (Denton and Karlén, 1973a; Porter, 1986; Grove, 1988). Additional records from regions that have previously been under-represented in global and hemispheric compilations are needed in order to understand better regional patterns of Holocene glaciation.

The Holocene glacial chronology of the tropical Andes is poorly understood relative to those derived for many temperate and polar regions (Clapperton, 1983; Clapperton and Sugden, 1988; Seltzer, 1990). Latest Holocene moraines in the Peruvian Andes are thought to either correlate with Little Ice Age (LIA) moraines of the Northern Hemisphere (Mercer and Palacios, 1977; Clapperton, 1981), or to predate them (Wright, 1984). In general, early and middle Holocene moraines have not been recognized in most parts of the tropical Andes (Clapperton, 1983). An exception to this is the Cordillera Blanca, northern Peruvian Andes, where Röthlisberger (1987) reported 14 radiocarbon dates from wood and buried soils in Holocene moraines, and concluded that in addition to ubiquitous LIA moraines, several localities have early and middle Holocene moraines. These dates make the Holocene moraine sequence in the Cordillera Blanca the most complete sequence in the tropical Andes (Clapperton and Sugden, 1988). However, because the 14 aforementioned dates are from five different valleys, we still do not have firm age control for a complete suite of Holocene moraines in any single valley. Moreover, many of these dates are from buried soils, and thus it is not clear how closely the dates constrain the ages of the till (Matthews and Dresser, 1983).

Lichenometry has proven to be a valuable technique for estimating the ages of Holocene moraines in many arctic and alpine regions (Locke *et al.*, 1979), but has yet to be employed in the tropical Andes. This paper reports on the use of lichenometry to refine the Holocene glacial chronology of the Cordillera Blanca.

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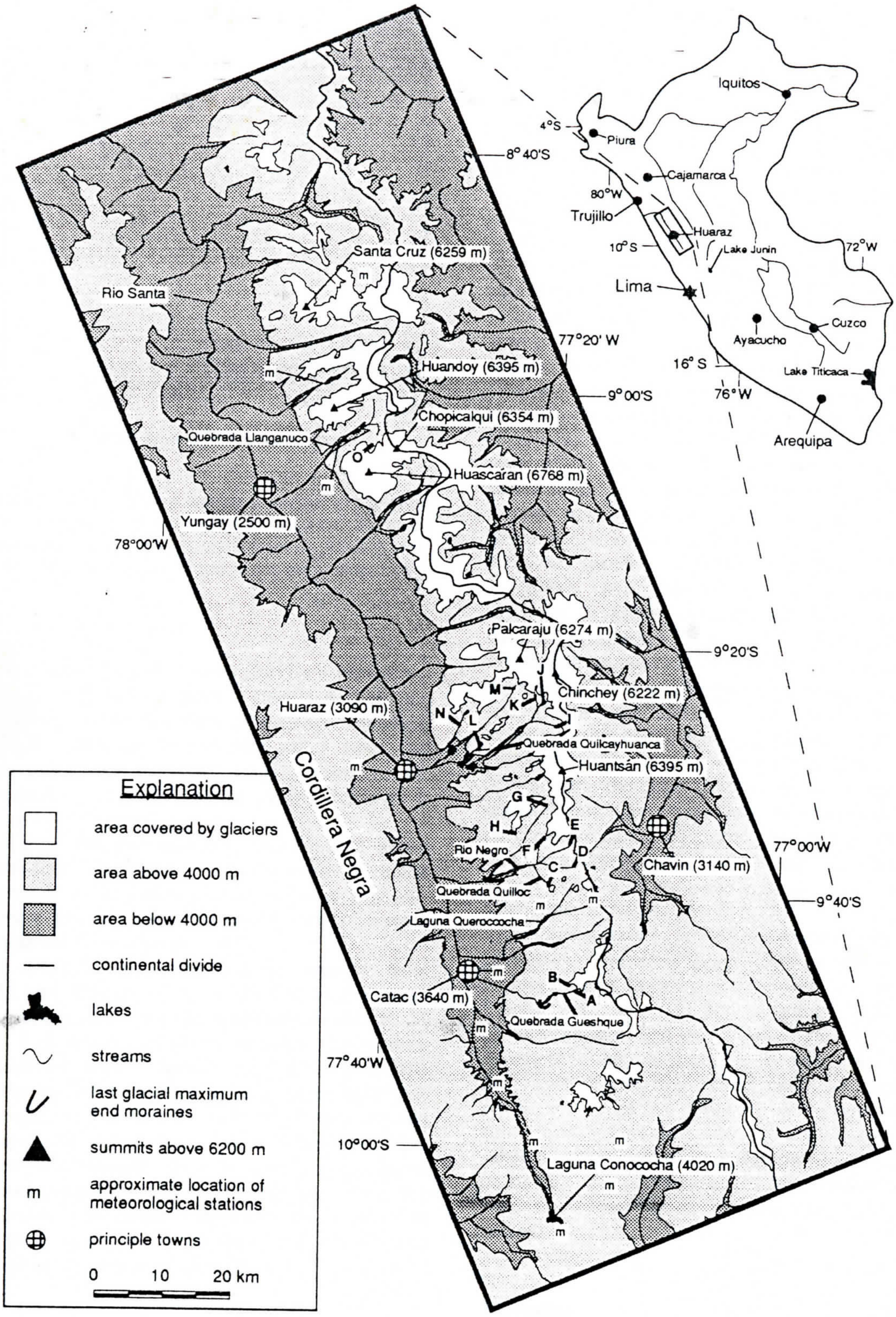

Figure 1 Location map of the Cordillera Blanca in north central Peru (modified from Díaz, 1988). Capital letters refer to cirques studied.

Study area and site factors

The Cordillera Blanca extends c. 225 km along the NW-SE trending Continental Divide in northern Perú (Figure 1). The core of the range is comprised primarily of Tertiary granodiorite, and the east and west flanks are composed of upper Mesozoic metasediments (Wilson *et al.*, 1967). These are predominantly amphibolite, hornfels, quartzite, and carbonates, and are particularly widespread in the southern portion of the range (Servicio Nacional de Geología y Minería, 1970). Late Quaternary glaciation has stripped the metasedimentary cover from the headwaters of most drainages, and thus Holocene moraines are primarily composed of granodiorite clasts. Exceptions to this are in the southern portion of the cordillera where cirques and Holocene moraines are composed primarily of hornfels and quartzite (cirques C-F, and I-K, Figure 1).

Holocene moraines are located between c. 4200 and

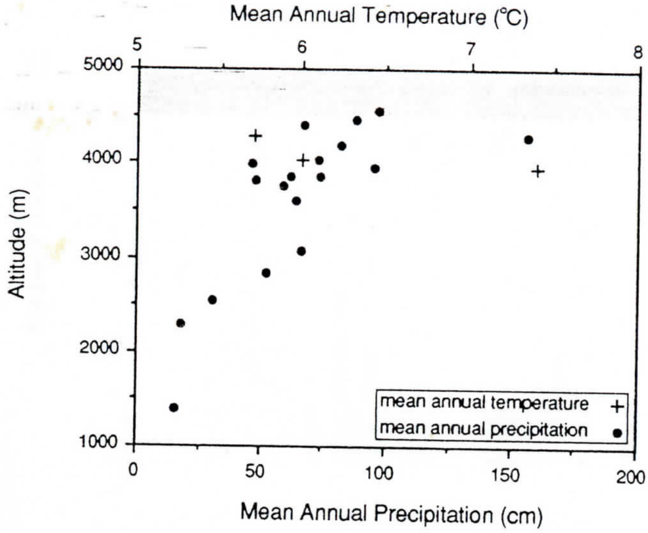

Figure 2 Mean annual temperature and mean annual precipitation versus altitude for meteorological stations on the west side of the Cordillera Blanca (data are unpublished and from the Huaraz office of Hydroandino). Shaded zone represents elevation of cirques A-O (Figure 1).

4650 m, and the lower limit of modern glaciers is between c. 4400 and 4900 m. Holocene moraines in cirques A-O (Figure 1) are multiple subparallel bouldery ridges that commonly stand c. 5–20 m above the surrounding valley floor. All Holocene moraine slopes are steep (>25°); those on the youngest moraines where ice-cored (e.g., cirque O, Figure 1) are unstable and near-vertical.

The limit of Holocene glaciation is several hundred metres above the tree-line. Vegetation is scarce on the youngest cirque moraines, but the oldest cirque moraines generally support a dense cover of sclerophyllous shrubs, tussock grasses and cushion plants (Smith, 1988).

Thirty- to 39-year-long meteorological records from between 3955 and 4550 m on the west side of the range indicate an average mean annual precipitation (MAP; 18 stations) of 81.5 cm and an average mean annual temperature (MAT; 3 stations) of 6.4°C (Figures 1 and 2). There is little seasonal variation in temperature, but precipitation is strongly seasonal; the dry season extends from May through November, and the wet season extends from December through April. Additionally, there is a strong altitudinal control on both temperature and precipitation. Thus the climatic conditions in the cirques (4500–5000 m) are likely to have been slightly cooler and wetter than those documented at the meteorological stations (Figure 2).

Methods

Lichenometry is based on the assumption that the largest lichen thallus living on a substrate can be used to indicate the length of time that the surface has been exposed to colonization and growth (Beschel, 1958; Benedict, 1967). Since the pioneering work of Beschel, numerous workers have employed lichenometry as a relative and numerical dating technique (reviewed in Locke *et al.*, 1979 and Innes, 1985). Numerical dating relies on the establishment of local lichen-growth curves, which have been developed both directly, by measuring the same thallus over several years (e.g., Miller and Andrews, 1972), and indirectly by measuring thalli sizes on deposits of known age (e.g., Benedict, 1967; 1981; 1985; Denton and Karlén, 1973b; Calkin and Ellis, 1980; Porter, 1981; Werner, 1990). Whereas direct measurements yield the most accurate growth rates, they are valid only for the time span of measurement. The indirect approach has been preferred by lichenometrists as mean growth rates can be estimated over much longer periods of time, thus partially circumventing the problem of short-term growth rate fluctuations due to environmental change (Innes, 1985).

The yellow-green crustose species *Rhizocarpon geographicum* is the most commonly reported lichen in such studies due to its ubiquity in arctic and alpine environments and to its slow growth rate (Locke *et al.*, 1979). However, owing to the impossibility of field identification to the species level (Werner, 1990), most workers have measured thalli from all the yellow-green *Rhizocarpon* lichens and reported these as *R. geographicum* sensu lato or *R. geographicum* agg. (Locke *et al.*, 1979). Innes (1985) recommended that the aforementioned terms be replaced with *Rhizocarpon* subgenus *Rhizocarpon*, and cautioned against the use of an aggregated *Rhizocarpon* 'species' growth curve as the growth rates of individual species are likely to differ (Innes, 1982).

Workers have generally used thallus diameter as a measurement of lichen size, however disagreements exist on sampling procedures. These include whether the short or long axis should be measured, whether the single largest thallus or the mean of the five or ten largest thalli should be considered, and whether the search for the largest thalli should be temporally or spatially limited (Locke *et al.*, 1979; Innes, 1985). Benedict (1985) contended that since the objective is to determine the oldest possible minimum age for a deposit, searches should not be spatially limited. In addition, Benedict (written communication, 1991) postulated that in order to find the thallus growing under optimal conditions, the single largest long axis measurement is the most appropriate lichenometric parameter.

The lichenometric procedures employed in this study are as follows: i) between 50 and 100% of the surficial boulders on moraines in 15 cirques on the west side of the Cordillera Blanca were searched for subgenus *Rhizocarpon* thalli; ii) both the short and long axes of nearly circular thalli were measured to the nearest 1 mm; iii) both the single largest and the mean of the five largest thalli are considered to be representative of the fastest growing lichens that initially colonized the moraine surface, and iv) growth rates for subgenus *Rhizocarpon* were determined by measuring thalli on surficial deposits whose ages are constrained by radiocarbon dates, pre-Colombian structures, and an historical record.

Results

Grouping of Holocene moraines on the basis of lichen sizes

Subgenus *Rhizocarpon* thalli form size groups that provide the basis for a four-fold subdivision of cirque moraines on the west side of the Cordillera Blanca (Figure 3). Clapperton (1972) subdivided the cirque moraines into two groups, termed group 3 (oldest) and group 4. I propose to name the Holocene moraines after the drainages in which they are best preserved; names are from the Recuay topographic map (Instituto Geográfico Nacional, 1983). These are, from oldest to youngest: Río Negro, Quilloc, Gueshque 1 and Gueshque 2. Río Negro terminal moraines are located between 4200 and 4650 m, or c. 300 m below the modern ice front, and Quilloc,

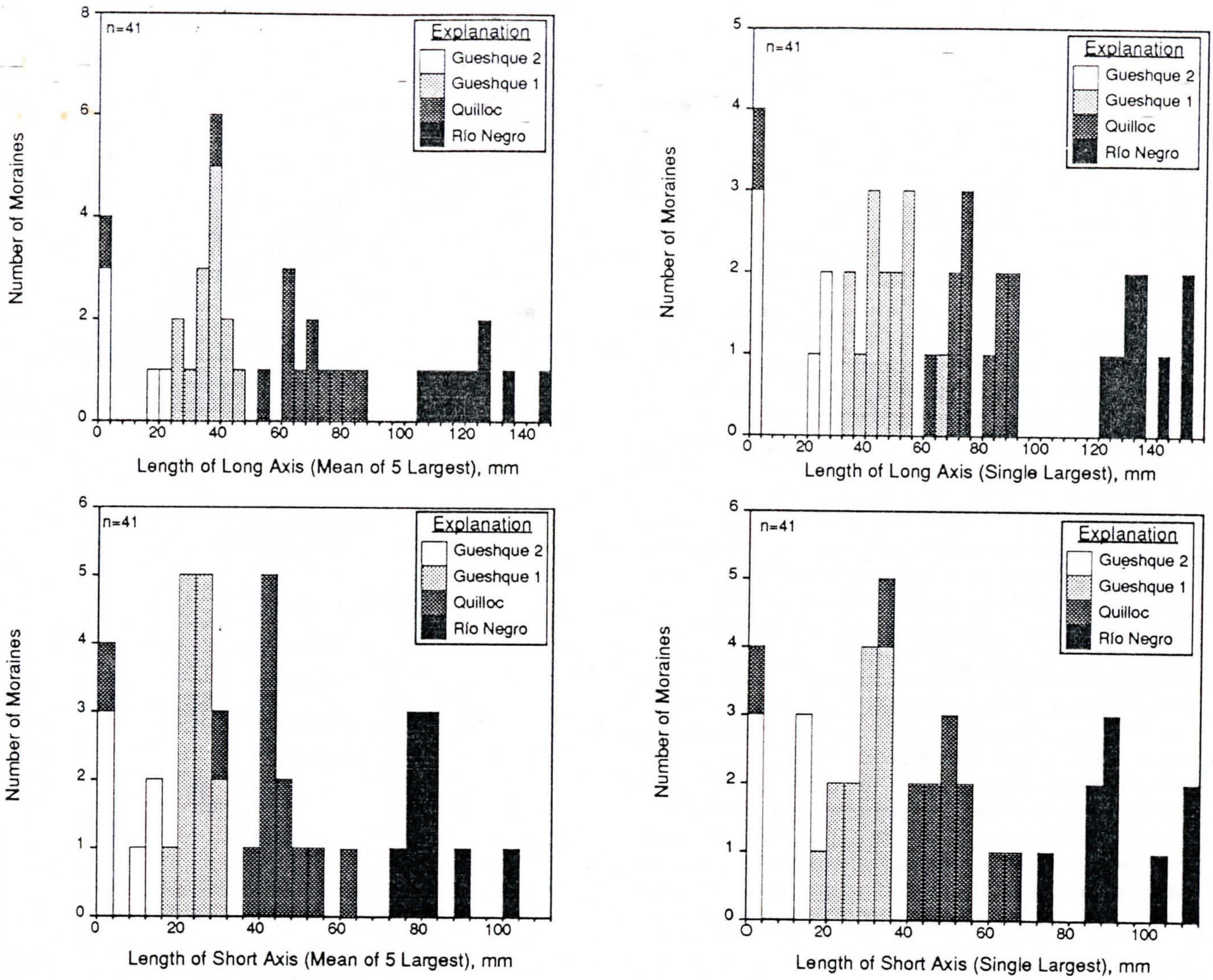

Figure 3 Histograms of moraine frequency versus lichen size. Most stratigraphic designations are based on lichenometry; apparently anomalous groupings are based on stratigraphic position and soil development (Rodbell, 1991).

Gueshque 1 and Gueshque 2 moraines are c. 250, 200 and 100 m below the modern ice front, respectively (Figure 4). In cirques D, G, H and L, only a cursory examination of subgenus *Rhizocarpon* thalli was made on Gueshque 2 moraines. Although this provides a basis for correlation, data are insufficient for use in histograms or numerical age determinations.

The degree of soil development on these moraines also supports their subdivision into a four-part sequence (Rodbell, 1991). In general, Río Negro moraines have subsurface horizon hues of 10YR, whereas Quilloc, Gueshque 1 and Gueshque 2 moraines have subsurface horizon hues of 2.5Y, 5Y, and 7.5Y, respectively.

Cirques A, B and D-I (Figure 1) contain the complete four-

Table 1 Summary of *Rhizocarpon* subgenus *Rhizocarpon* parameters

Moraine group	Mean of five largest as a per cent of maximum[1]		Long: short axis ratio[1]		Granite: metamorphic ratio[2]	
	short axis	long axis	Mean of five largest	Single largest	Mean of five largest	Single largest
Gueshque 1	90.3 ± 5.7	90.0 ± 5.0	1.67 ± 0.22	1.69 ± 0.34	1.22 ± 1.05	1.25± 0.96
Gueshque 2	87.5 ± 6.3	81.6 ± 10.1	1.51 ± 0.16	1.64 ± 0.23	1.18 ± 1.05	1.12 ± 0.91
Quilloc	91.3 ± 4.2	88.2 ± 6.1	1.49 ± 0.17	1.55 ± 0.19	1.11 ± 1.08	1.11 ± 1.06
Río Negro	89.2 ± 5.1	90.9 ± 5.8	1.50 ± 0.09	1.46 ± 0.11	0.89 ± 0.88	0.83 ± 0.93

[1] mean is average from all sites, uncertainty is $\pm 1\sigma$
[2] ratio is mean from all moraines with granitic clasts/mean from all moraines with metamorphic clasts

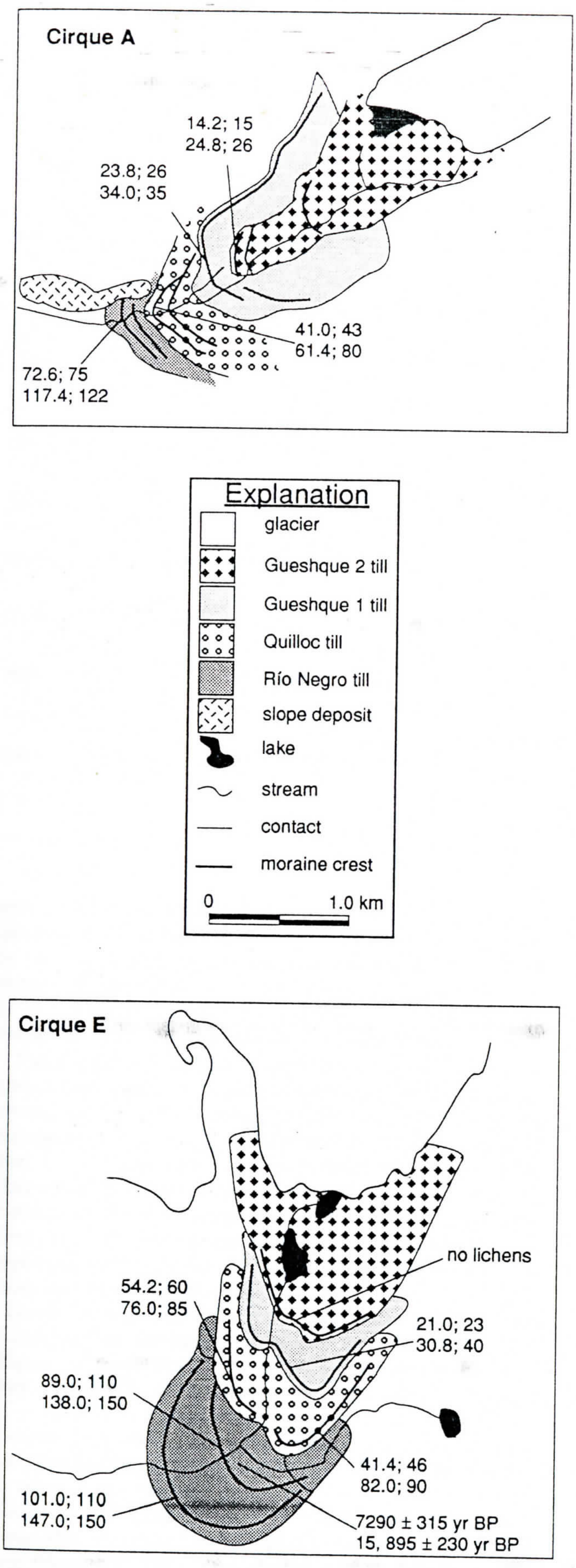

Figure 4 Maps of moraines in cirques A and E (Figure 1) from 1:25 000 air photos. The numbers plotted are the mean of the five largest and single largest short-axis measurements, and the mean of the five largest and single largest long-axis measurements.

part sequence of moraines, whereas cirques C and J-O are missing one or more of the moraines. This latter may be due to the erosion of older moraines by younger glacial advances (cirques J, K and O), or burial of moraines by colluvium (cirque C), or to the submergence of moraines in a lake basin (cirque L). In general, cirque floors slope more gently in the southern portion of the range (e.g., cirques A-H) resulting in greater lateral distance between moraine groups and thus enhanced preservation of older moraines.

Lichen parameters

Of the four indices of thallus size considered, plots of the mean of the five largest thalli result in more compact groups of moraines than do plots of the single largest thallus (Figure 3). The mean of the five largst thalli for both short- and long-axis data averages about 90% of the size of the single largest thalli (Table 1). Thus, in most cases, inherited thalli have probably not been included in the data set. However, the likelihood of recognizing such thalli is inversely related to both substrate age and the number of anomalous thalli present (Innes, 1985), and thus it is probable that some inherited thalli have been included in this study.

The ratio of the length of long axis to that of the short axis (L/S ratio) is a rough measure of the circularity of the thalli measured. The L/S ratio for the mean of the five largest thalli decreases from 1.67 on Gueshque 2 moraines to c. 1.5 on all older moraines, and the mean from all sites is 1.52 ± 0.15 (± 1σ; Table 1). Similarly, the L/S ratio for the single largest thallus decreases from 1.69 on the youngest moraine group to 1.46 on the oldest moraine group, while the mean from all sites is 1.56 ± 0.21. Although t-test results indicate that these trends are not statistically significant at the 0.05 confidence level, these data suggest that lichen thalli may be more circular on progressively older moraines.

Effect of substrate lithology

Within each moraine group, the ratio of the size of subgenus *Rhizocarpon* thalli on moraines composed of granodiorite clasts to those on moraines composed of metasedimentary clasts (G/M ratio) suggests that substrate composition is a factor controlling thalli size (Table 1). The G/M ratio for all indices of lichen size decreases on successively older moraine groups, however this trend is not statistically significant at the 0.05 confidence level. On the three youngest moraine groups lichen thalli are generally larger on granodiorite substrates than on metasedimentary substrates. Moreover, this disparity generally decreases with increasing age of moraine such that thalli on all Río Negro moraines are larger on metasedimentary substrates than on granodiorite substrate (Table 1). This relationship is not easily explained. Perhaps subgenus *Rhizocarpon* needs more time to colonize the fine-grained metasedimentary rocks than the coarse-grained granodiorite rocks, yet once colonized, thalli on the former rock type grow faster. If so, this would support the contention of Benedict (1967) that rock texture is an important control on the growth rate of subgenus *Rhizocarpon* in the Front Range, Colorado. He found that fine-grained or glacially-polished rocks retain less moisture and are colonized more slowly than coarse-grained rocks. With time, however, granular disintegration of coarse-grained rocks may impede the growth of thalli, and thereby result in larger thalli on fine-grained rocks (Benedict, 1967).

Lichen growth curve

Nine high-altitude sites (>3800 m) were used indirectly to estimate the growth rate of subgenus *Rhizocarpon* thalli on the west side of the Cordillera Blanca, Perú (Table 2). Six

Table 2 Data used for *Rhizocarpon* subgenus *Rhizocarpon* growth curves

Site (elevation m)	Substrate lithology	Short axis mean of five largest thalli (mm)	Short axis single largest thalli (mm)	Long axis mean of five largest thalli (mm)	Long axis single largest thalli (mm)	Estimated Age yr BP	References
flood deposit, cirque M (4450)	granodiorite	11.8	13	19.0	20	14 ± 0	Bartle, 1981
pre-Colombian stone buildings, Quebrada Quilcayhuanca (3900)	metamorphic	21.0	28	36.8	46	1000 ± 250	R.L. Burger, written comm., 1989 Caesar Aguirre, per. comm., 1988
pre-Colombian stone walls, Quebrada Quilcayhuanca (3900)	metamorphic	33.8	37	55.6	70	1000 ± 250	R.L. Burger, written comm., 1989 Caesar Aguirre, pers. comm., 1988
Gueshque 1 moraine, cirque K (4600)	metamorphic	23.8	25	39.2	45	<1170 ± 50	Röthlisberger, 1987; Hv-11277
Gueshque 1 moraine, cirque J (4350)	metamorphic	20.2	22	33.4	42	<1365 ± 65	Röthlisberger, 1987; Hv-8708
Quilloc moraine, cirque N (4325)	granodiorite	60.6	65	85.6	90	>4105 ± 70	Röthlisberger, 1987; Hv-11276
Quilloc moraine, cirque C (4675)	metamorphic	39.2	40	55.0	60	≈1575 ± 170	this study; GX-14354
inner Río Negro moraine, cirque E (4275)	metamorphic	89.0	110	138.0	150	>7290 ± 315	this study; GX-14598
outer Río Negro moraine, cirque E (4275)	metamorphic	101.0	110	147.0	150	>7290 ± 315	this study; GX-14598

sites are moraines whose ages are constrained by radiocarbon dates, two are archaeological sites with age estimates made by two archaeologists, and one is a historically dated flood deposit. In the following pages, I give two dimensions (e.g., 12 × 19 mm). These represent the means of the five maximum short-axis and long-axis measurements.

The presence of 12 × 19 mm thalli on boulders deposited from a December, 1941 flood at 4500 m in Quebrada Cojup (cirque M, Figure 1) suggests that the time required for the colonization of subgenus *Rhizocarpon* on granodiorite is less than c. 50 years (Table 2). However, these boulders were likely stabilized upon deposition whereas boulders on ice-cored moraines may require several tens of years to stabilize. Thus, the size of subgenus *Rhizocarpon* thalli on moraines deposited within the last c. 50 years could be smaller than those documented at this site.

Stone buildings and walls in the lower portion of Quebrada Quilcayhuanca are estimated to date from 800 to 1200 BP (Figure 1; Table 2) (R.L. Burger, written communication, 1989). However, no detailed study of these sites has been made, and such an age range can only be considered as a preliminary estimate. The stones used in the construction of the small buildings appear to have been sufficiently modified by man to preclude the presence of many inherited thalli. However, the stone walls were constructed from largely unmodified stones and may support numerous inherited thalli (e.g., Benedict, 1967). Thus, the 34 × 56 mm thalli on these walls should be considered a maximum limiting size for the c. 1000 BP portion of the growth curve; the 21 × 37 mm thalli on the buildings is probably more representative. Furthermore, this site is several hundred metres lower than most cirque moraines, thus lichens there have probably been growing in a slightly drier and warmer environment than those in the cirques. Because of these problems, these structures can only be used to broadly constrain the growth rate curve of subgenus *Rhizocarpon* thalli.

Two dates from Röthlisberger (1987) are from soil humus and wood buried by till in Quebrada Quilcayhuanca. These provide maximum limiting ages for Guesque 1 moraines in cirques J and K (Figure 1). Both moraines are composed entirely of fine grained metasedimentary clasts. A large subgenus *Rhizocarpon* population is present on the moraine in cirque K, but few thalli were found on the moraine in cirque J. Consequently, whereas the date of 1170 ± 50 BP (Hv-11277) in cirque K provides a maximum age for 24 × 40 mm thalli on metamorphic clasts, that of 1365 ± 65 BP (Hv-8708) in cirque J provides a maximum age for thalli that are probably larger than the recorded 20 × 33 mm.

Thalli on the Quilloc moraine in cirque C provide the best data for the pre-historic portion of the growth curve (Figure 1). The moraine is composed entirely of peat folded into an anticline and mantled by numerous metasedimentary erratics which contain a small population of subgenus *Rhizocarpon* thalli. A sample of the stratigraphically highest portion of the peat bed yielded a date of 1575 ± 170 BP (GX-14354). Because the elevation of the outlet of the small lake in this cirque is controlled by a bedrock lip, the peat probably grew in the lake basin until it was ploughed into its present configuration by a glacial advance that culminated no earlier than 1575 ± 170 BP. Thus, this date provides a close limiting age for the moraine and for the 39 × 55 mm thalli on it; this date is preferred to those for the moraines in cirques J and K in constructing the growth curve.

A radiocarbon date of 4105 ± 70 BP (Hv-11276; Röthlisberger, 1987) from the base of a fen on a Quilloc moraine at 4325 m in cirque N (Figure 1) provides age control for the middle-Holocene portion of the curve. This date provides a minimum age estimate for the moraine (Röthlisberger, 1987), and for the 61 × 86-mm thalli growing on it (Table 2).

The oldest portion of the lichen growth curve is constrained by a radiocarbon date from the base of a fen that is located several hundred metres upvalley from two Río Negro moraines in cirque E (Figures 1 and 4; Table 2). The >125μ, macroorganic material yielded an age of 7290 ± 315 BP (GX-14598), whereas the <125μ disseminated organic fraction yielded an age of 15 895 ± 230 BP (GX 14598-A). The disparity of c. 8600 years is probably the result of contamination of the fine fraction by coal present in the Cretaceous Chimú Formation which comprises part of the bedrock in this cirque (Servicio Nacional de Geología y Minería, 1970). The inner of the two moraines has subgenus *Rhizocarpon* thalli of 89 × 138 mm whereas those on the outer moraine are 101 × 147 mm (Figure 4). Thus, the thalli on the Río Negro moraines in cirque E have apparently not reached senescence, and hence the lifespan of subgenus *Rhizocarpon* in this area may be more than c. 7500 years.

Whereas little is known of the lifespan of subgenus *Rhizocarpon* in the tropics, its lifespan is estimated to be c. 9500 years on Baffin Island, Canada (280 mm-single-largest thalli; Miller and Andrews, 1972), at least 4500 years in the Brooks Range, Alaska (150-mm thalli; Calkin and Ellis, 1980), at least 3500 years in the Wrangell and St Elias Mountains, Alaska (150-mm thalli; Denton and Karlén, 1973b), and greater than 7000 years in the Front Range, Colorado (257-mm thalli; Benedict, 1985). Thus, the size of the largest subgenus *Rhizocarpon* thalli noted in this study (150 mm) compares reasonably well with the maximum size observed elsewhere; however thalli in this area may require more time to attain this size. Finally, differences in rock type that affect the rate of rock weathering between the aforementioned study areas may account for the differences in maximum thalli size (J.L. Innes, written communication, 1991).

Plots of four indices of thallus size against approximate age of substrate illustrate the general growth pattern of subgenus *Rhizocarpon* on the west side of the Cordillera Blanca (Figure 5). The growth curves were constructed using the four growth stations with the best age control and the largest

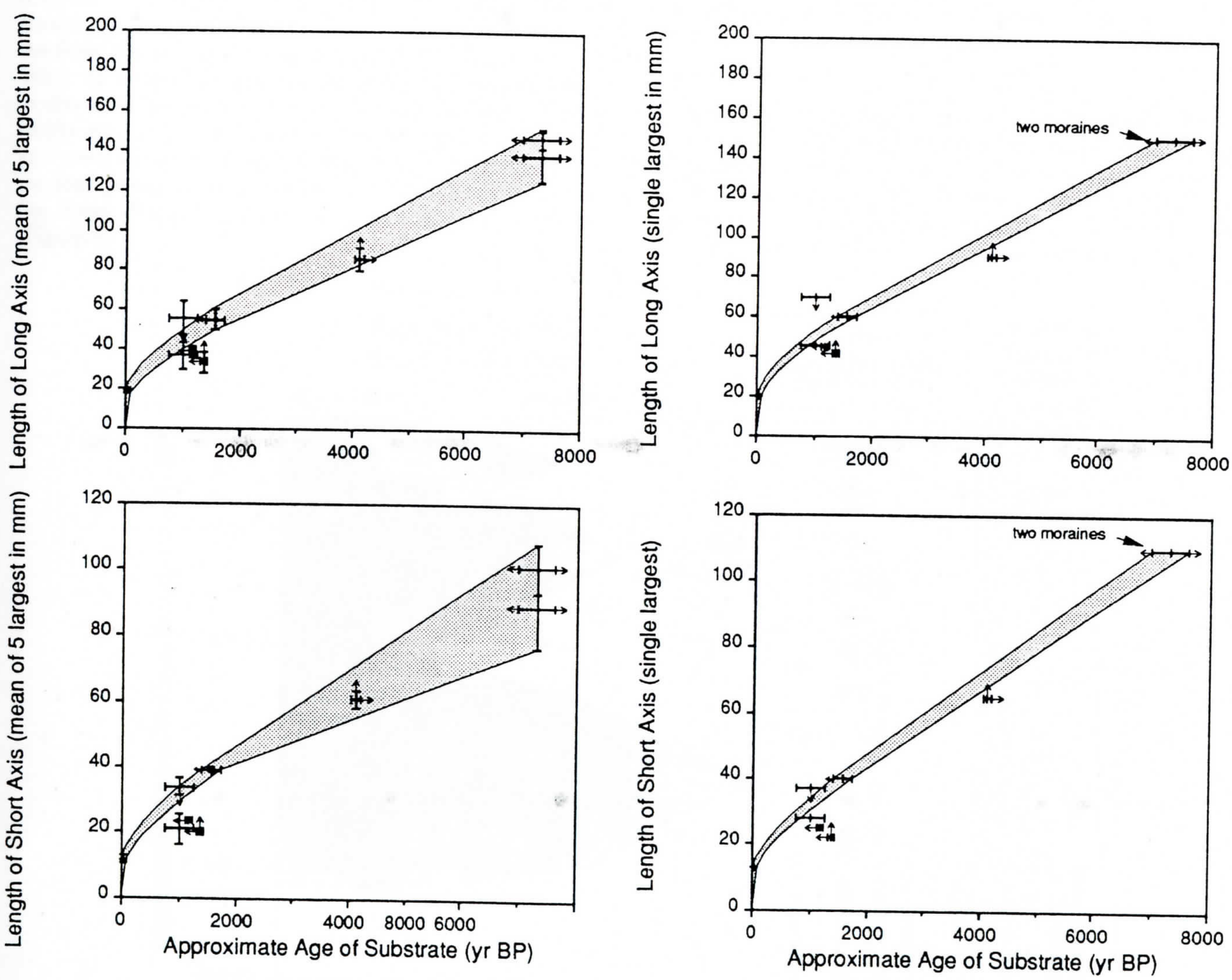

Figure 5 Preliminary growth curves of *Rhizocarpon* subgenus *Rhizocarpon* for the west side of the Cordillera Blanca, Perú. Error bars for radiocarbon dates are ± 1σ. Arrows pointing to the left indicate that radiocarbon date provides a maximum-constraining age for the moraine, whereas those pointing to the right indicate that date provides a minimum-constraining age for the moraine. The arrow pointing up indicates that the lichen population on moraine in cirque K is anomalously small, whereas that pointing down indicates that stone walls in Quebrada Quilcayhuanca likely contain inherited thalli.

subgenus *Rhizocarpon* populations. These are the 1941 flood deposit and the radiocarbon age-constrained moraines in cirque C (≈1575 ± 170 BP), cirque N (>4105 ± 70 BP), and cirque E (>7290 ± 315 BP). Because the other four localities are poorly dated and/or have only small subgenus *Rhizocarpon* populations, they provide only broad constraints on the form of the growth curve. The inferred growth curves are preliminary, and will likely be modified as additional data are acquired.

An initially rapid period of growth lasting at least 50 years is followed by a c. 500 to 1000 year-long phase of decelerating growth, and thence by a period of slow growth beginning at or slightly after c. 1000 years. In the initial, rapid phase of growth, thalli grow c. 0.4 mm yr^{-1} (maximum long axis) compared to c. 0.016 mm yr^{-1} in the slow-growth part of the curve. Growth curves of this general shape have been noted by numerous lichenometrists in areas with <100 cm MAP (e.g., Miller and Andrews, 1972; Denton and Karlén, 1973b; Calkin and Ellis, 1980; Benedict, 1985; Werner, 1990).

Although the growth curve for subgenus *Rhizocarpon* on the west side of the Cordillera Blanca is similar to several curves from other alpine regions with <100 cm MAP, significant differences are apparent (Figure 6). The rate of thallus growth during the initial, rapid phase is faster in this study area (c. 0.40 mm yr^{-1}) than in southern Alaska (c. 0.15 mm yr^{-1}; Denton and Karlén, 1973b), the Brooks Range, Alaska (c. 0.11 mm yr^{-1}; Calkin and Ellis, 1980) and the Front Range, Colorado (c. 0.23 mm yr^{-1}; Benedict, 1967; 1981). In contrast, growth rate during the slow phase is lower in this study area (0.016 mm yr^{-1}) than in southern Alaska (0.034 mm yr^{-1}), the Brooks Range, Alaska (0.030 mm yr^{-1}) and the Front Range, Colorado (0.029 mm yr^{-1}). Of the four growth curves, those for the Cordillera Blanca and the Front Range, Colorado have the greatest similarity (Figure 6).

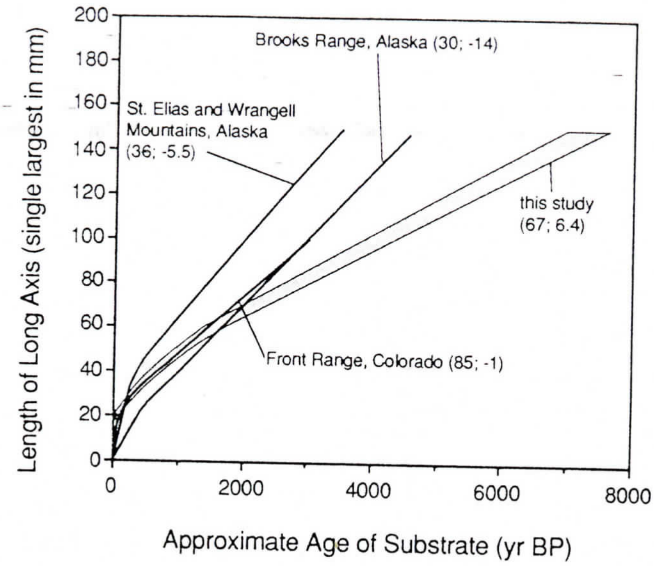

Figure 6 Comparison of *Rhizocarpon* subgenus *Rhizocarpon* growth curves from the St Elias and Wrangell Mountains, Alaska (Denton and Karlén, 1973b), Brooks Range, Alaska (Calkin and Ellis, 1980), Front Range, Colorado (Benedict, 1967; 1981), and this study. Numbers in parentheses refer to the estimated mean annual precipitaiton and mean annual temperature, respectively, at each site.

Although the Cordillera Blanca and the Front Range, Colorado also have the two most similar climates, no obvious relationship is apparent between lichen growth rate and MAP or MAT for the four areas. However, MAP and MAT may not be the two most important climatic variables controlling lichen growth rates as microclimate, particularly moisture

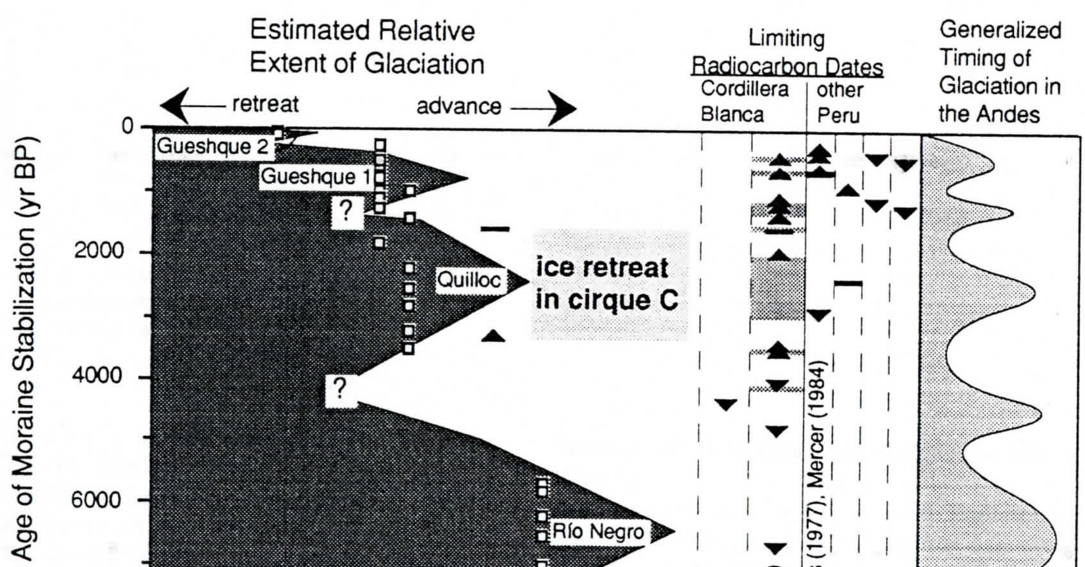

Figure 7 Comparison of the timing and relative extent of Holocene glaciation in the Cordillera Blanca based on lichenometry (symbolized by open squares), with radiocarbon age-constrained moraines from this and other studies in Peru (solid triangles). Stippled pattern in column of Röthlisberger (1987) indicates suggested timing of glaciation in the Cordillera Blanca. Triangles pointing down indicate minimum-limiting radiocarbon date, and those pointing up indicate maximum-limiting radiocarbon date. Solid bars denote dates that directly date glacial advance.

Table 3 *Rhizocarpon* subgenus *Rhizocarpon* thalli measurements and estimated age of moraine stabilization from the long axis growth curves

Moraine Group[1]		Site	Rock type[2]	Short axis max. (mm)	Short axis mean (mm)	Long axis max. (mm)	Long axis mean (mm)	Age[3]
Gueshque 1	A	QG1	g	15	12.6	20	18.0	50
	B	QG5	g	15	14.2	26	24.8	100
	I	QQ2	m	15	11.0	24	20.4	100
Gueshque 2	G	RN21	g	32	29.2	42	37.6	625
	A	QG2	g	34	28.8	50	39.0	975
	B	QG6	g	26	23.8	35	34.0	400
	I	QQ3	m	28	23.4	54	42.6	1100
	I	QQ4	m	30	27.0	55	46.8	1225
	K	QQ6	m	25	23.8	45	39.2	750
	J	QQ8	m	22	20.2	42	33.4	625
	L	QC1	g	30	27.4	45	42.4	750
	O	QL	m	35	25.8	65	39.4	1800
	E	RN3	m	23	21.0	40	30.8	550
	F	RN8	m	35	27.0	55	38.0	1225
	D	RN12	m	29	24.6	38	34.2	475
	C	RN15	m	18	16.8	32	24.2	250
Quilloc	G	RN20	m	33	30.6	50	39.6	975
	H	RN29	g	48	40.8	75	65.0	2550
	A	QG4	g	55	46.6	75	69.0	2500
	B	QG7	g	43	41.0	80	61.4	2800
	L	QC2	g	53	49.4	75	72.0	2550
	O	QL2	g	45	43.2	70	62.0	2225
	E	RN4	m	46	41.4	90	82.0	3500
	E	RN5	m	60	54.2	85	76.0	3225
	D	RN13	m	50	43.6	85	68.6	3225
	C	RN16	m	40	39.2	60	55.0	1425
	F	RN9	m	50	45.4	70	63.8	2225
	O	QLL1	g	65	60.6	90	85.6	3500
Río Negro	H	RN28	g	85	79.0	130	106.0	6200
	A	QG3	g	85	77.2	135	115.0	6525
	B	QG8	g	75	72.6	122	117.4	5650
	K	QQ7	m	100	82.0	130	127.0	6200
	E	RN7	m	110	89.0	150	138.0	7300
	E	RN6	m	110	101.0	150	147.0	7300
	D	RN14	m	90	81.0	140	124.0	7300
	F	RN11	m	90	79.0	125	111.0	5800
	I	QQ5	m	90	80.0	135	121.0	6525

[1] capital letters to the right of each moraine group refer to particular cirques
[2] g=granodiorite; m=metamorphics
[3] estimated age from long-axis curve (yr BP)

availability, may have a strong effect on growth rate (Benedict, 1967; 1990). The strong seasonality of precipitation and/or the strong diurnal temperature variations in the Cordillera Blanca may result in far lower growth rates after c. 1500 years than would otherwise be expected from the MAP and MAT data alone. In addition, Holocene climatic fluctuations may not have been of the same relative magnitude in the four areas, and thus one should not expect to find a close relationship between modern climatic parameters and lichen growth rates. Finally, given the paucity of age control data in the present study and the uncertainties involved in some dates from all four areas, detailed comparisons between the four curves may not be justified. Additional data are needed from the west side of the Cordillera Blanca in order to more firmly establish the slope and duration of the decelerating and linear phases, and to better estimate the life span of subgenus *Rhizocarpon*.

Timing of Holocene glaciation in the Cordillera Blanca

In order to estimate ages of moraine stabilization, ages were graphically derived using the growth curve for the single largest long axis data (Table 3). In general, the lichenometric age estimates suggest four periods of Holocene glacier advances, each slightly less extensive than the previous one (Figure 7). It is not possible to estimate the extent of ice retreat between these advances. One extreme would be that each moraine represents a minor stillstand in an otherwise steady ice retreat from the Río Negro ice position, whereas the other extreme calls for complete deglaciation between successive advances. In addition, moraine groups in many cirques are comprised of several moraines, thus reflecting multiple ice positions during each period of Holocene glacier expansion.

If the time necessary for moraine stabilization is assumed to be on the order of several tens of years and if lichen colonization takes a similar amount of time, then the results of this study likely underestimate the ages of moraines by as much as c. 100 years. Interpretation of the lichen growth curve suggests that Río Negro moraines represent glacier positions in the early Holocene, and those of the three younger moraine groups represent ice positions within the last c. 3.5 ka (Table 6; Figure 7). Gueshque 2 moraines were deposited within the last c. 200 years and many of these were probably stabilized during the rapid ice retreat that occurred during the late nineteenth and early twentieth centuries (Broggi, 1943; Clapperton, 1972).

Comparison with radiocarbon-age-constrained moraines in the Cordillera Blanca is hindered because it is rarely possible to estimate the degree to which limiting radiocarbon dates underestimate or overestimate the true age of the moraine. For example, the interpretation that the Río Negro moraines are early Holocene is equivocal because it is based on only the c. 7.3 ka-minimum-limiting-radiocarbon date. Thus, the Río Negro moraines could be pre-Holocene. However, the early Holocene age is preferred because soil and rock weathering criteria clearly distinguish the Río Negro moraines from the late Pleistocene moraines (10–13.5 ka) in the Cordillera Blanca (Rodbell, 1991). In addition, Clapperton (1981; 1983) suggested that his 4287 ± 90 BP date provides a close minimum-limiting age for a glacial advance that deposited Río Negro moraines at Yurac Coral (3850 m) in Quebrada Llanganuco (Figure 1). However, these moraines are several hundred metres lower than the early Holocene moraines dated by Röthlisberger (1987) or mapped in this study. Holocene ELA variations of this magnitude are unlikely, and thus the Yurac Coral moraines are more likely pre-Holocene, considerably older than the above radiocarbon date (Figure 7) (Clapperton and Sugden, 1988).

The remaining dates from the Cordillera Blanca are from Röthlisberger (1987) and this study, and all provide limiting dates for moraines that lie between 4000–4700 m. Thalli were measured on moraines whose ages are constrained by six of these dates, and thus correspondence between the date and the lichenometric moraine group is firm. However, five of these six dates were used to construct the growth curve of subgenus *Rhizocarpon*, and thus they do not provide an independent test of the moraine chronology based on lichenometry. The fifth date is from the peat composing the Quilloc moraine in cirque C (Figure 1). The sample was taken from several metres below the surface from near the base of the peat; it yielded a date of 3360 ± 95 BP (GX-14355). This date provides a maximum limiting age for the Quilloc moraines, and in conjunction with the 1575 BP date from the top of the peat indicates that the ice extent in cirque C must have been at or above the pond adjacent to the moraine between c. 3350–1600 BP. This latter age conflicts with the lichenometrically-derived ages for numerous Quilloc moraines (Figure 7). Thus, the lichenometric ages for the numerous other Quilloc moraines may be too old due to errors in the growth curve. Alternatively, the glacier in cirque C may have had a history not synchronous with glaciers in the other cirques studied. Although the remaining dates from Röthlisberger (1987) cannot be precisely correlated with the lichenometric moraine groupings, they generally support the chronology presented here (Figure 7).

Comparison of the Holocene chronology of glaciation in the Cordillera Blanca with radiocarbon-age-constrained moraines from other areas in Perú indicates that the former represents the longest record of Holocene glaciation previously recognized in the Peruvian Andes (Clapperton and Sugden, 1988). Apart from the Cordillera Blanca, no dates from the Peruvian Andes provide strong evidence for an early Holocene glacial advance. Radiocarbon dates from peat near the southern dome of the Quelccaya ice cap indicate that the ice cap was smaller than it is today between 2670 ± 95 and 1625 ± 85 BP (Mercer and Palacios, 1977). These dates are consistent with the dates from the peat moraine in cirque C, and further suggest that the Quilloc moraines may be younger than c. 1600 BP. However, Clapperton (1983) reported that the maximum age of a moraine in the Cordillera Raura is closely constrained by a date of 2375 ± 35 BP. Thus, the age of the Quilloc moraines and the regional significance of the two sets of peat dates are an enigma.

The remaining radiocarbon dates from the Peruvian Andes generally support the moraine chronology from the Cordillera Blanca (Figure 7). The LIA is a prominent feature of the oxygen isotope record from the Quelccaya Ice Cap where it is dated at AD 1500–1900 (Thompson *et al.*, 1985, 1986; Grootes *et al.*, 1989). Gueshque 2 and Gueshque 1 moraines were likely deposited during this interval as was the Huancané I moraine near the Quelccaya Ice Cap (270 ± 80 BP, Mercer and Palacios, 1977). In contrast, Wright (1984) contended that the youngest moraines in central Perú all predate 1100 ± 70 BP, and thus are not correlative with the LIA of the Northern Hemisphere. This is based on relatively few radiocarbon dates, and is not easily reconciled with the abundant evidence from southern and northern Perú for glacier advances during the LIA.

The chronology presented here is in agreement with the generalized timing of Holocene glaciation throughout the Andes as summarized by Clapperton (1983) and Clapperton and Sugden (1988) (Figure 7). Data from these reviews, and that by Burrows (1979), indicate that throughout the Southern Hemisphere there is abundant evidence of at least one early Holocene glacial advance, although the precise timing of this advance may not be the same everywhere. In contrast to the models of Clapperton (1983) and Clapperton and Sugden (1988), and because the aforementioned c. 4.3 ka date of Clapperton (1981) can no longer be considered to constrain the age of Holocene moraines, there is little evidence from the Peruvian Andes that strongly supports the existence of moraines dating to c. 5–4 ka (Figure 7). Data from several studies in the Andes indicate that moraines dating to the last several hundred years are ubiquitous and that some of these probably correlate with the Little Ice Age moraines of the Northern Hemisphere (Grove, 1988). Although improvements have been made, the dating of moraines in the Andes remains too imprecise to evaluate whether glacier activity there has been synchronous across the region, or with other arctic and alpine regions over the last c. 10 ka.

Conclusions

The mapping of moraines in the Cordillera Blanca and the concomitant measurement of their *Rhizocarpon* subgenus *Rhizocarpon* thalli supports a four-fold Holocene glacial chronology. A lichen-growth curve based on the size of thalli on radiocarbon-age-constrained moraines, a historical flood deposit and prehistoric structures suggests that: i) subgenus *Rhizocarpon* thalli can colonize stabilized substrata in less than c. 50 yr; ii) the initial rapid growth phase of subgenus *Rhizocarpon* thalli is faster, and the subsequent phase is slower in this area relative to curves for several other alpine regions, and iii) the age of stabilization of deposits above c. 4000 m on the west side of the Cordillera Blanca can be estimated for the last c. 8 ka.

The growth rate of subgenus *Rhizocarpon* indicates that Río Negro moraines were stabilized between c. 7000 and 6000 BP; and that Quilloc, Gueshque 1 and Gueshque 2 moraines stabilized between c. 3350 and 1800 BP, between 1250 and 400 BP, and within the last several hundred years BP, respectively. These age estimates are generally supported by radiocarbon dates from the Cordillera Blanca and other cordillera in Perú, and support the concept of widespread early Holocene and LIA glacial advances. The lichenometric age of Quilloc moraines conflicts with radiocarbon dates from peat in the Cordillera Blanca and in the vicinity of the Quelccaya Ice Cap but is supported by a radiocarbon-age-constrained moraine in the Cordillera Raura. Additional data are needed to resolve this apparent conflict, and to further refine the growth curve of subgenus *Rhizocarpon* in the Cordillera Blanca.

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