GEOLOGICAL SURVEY OF CANADA
BULLETIN 394

A LICHENOMETRIC STUDY OF HOLOCENE ROCK GLACIERS AND NEOGLACIAL MORAINES, FRANCES LAKE MAP AREA, SOUTHEASTERN YUKON TERRITORY AND NORTHWEST TERRITORIES

Arthur S. Dyke

1990

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Critical Reader
O.L. Hughes

Cover description

A rock glacier composed of limestone rubble displaying typical transverse arcuate ridges and furrows near the Yukon - Northwest Territories border south of Tungsten.

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Preface

Rock glaciers and Neoglacial moraines are common features of the alpine zones of Canada, both in the Cordillera and in the mountains of the eastern Arctic. These features contain a record of changing environmental conditions during postglacial time - generally the last 10 000 years, and primarily the last 5000 years. The arctic and alpine landscapes are geomorphically sensitive to environmental change because these environments are near critical geomorphic thresholds. Examples of critical thresholds are summer snowline elevation and the 0°C summer ground temperature. If the summer snowline fails to rise above the highest land, glaciers will form; if thick debris on steep slopes remains frozen during successive summers, permafrost will form and give rise to slow flow of frozen debris as rock glaciers. But these are not the only thresholds and climate is not the only control. It is becoming increasingly important to understand how geomorphic activity is controlled by geological and environmental conditions and how it has responded to climatic fluctuations. By understanding how environmental systems have responded to past changes, we can assess the impact of future environmental changes. This study addresses these issues in the northeastern Cordillera and is a by-product of a regional Quaternary geology mapping program reported in a companion report as GSC Memoir 426.

Elkanah A. Babcock
Assistant Deputy Minister
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Préface

Les glaciers rocheux et les moraines néoglaciaires sont des formes courantes des zones alpines du Canada, que ce soit dans la Cordillère ou dans les montagnes de l'Arctique oriental. Ces formes contiennent des indices de conditions environnementales changeantes au cours de la période post-glaciaire, soit en général les 10 000 dernières années, et principalement les 5000 dernières années. Les paysages arctiques et alpins présentent une géomorphologie sensible aux changements qui surviennent dans l'environnement étant donné que ces environnements comportent des seuils géomorphologiques quasi critiques. Comme exemples de seuils critiques, on peut noter la hausse de la limite des neiges persistantes en été et la température estivale du sol à 0°C. Si la limite des neiges persistantes ne s'élève pas en été au-dessus des terres les plus élevées, des glaciers se forment; si les débris épais accumulés sur les versants abrupts demeurent gelés pendant plusieurs étés, un pergélisol se forme et cause la lente coulée des débris gelés sous forme de glaciers rocheux. Mais ce ne sont pas là les seuls seuils et le climat n'est pas non plus le seul facteur de contrôle. Il est de plus en plus important de comprendre comment l'activité géomorphologique est contrôlée par la géologie et les conditions du milieu et comment elle répond aux fluctuations climatiques. En sachant comment les systèmes environnementaux ont répondu aux changements passés, il est possible de prévoir les répercussions des changements environnementaux futurs. La présente étude traite de ces questions en les appliquant au nord-est de la Cordillère, et elle est un sous-produit d'un programme de cartographie régional de la géologie quaternaire mentionné dans un rapport connexe comme le mémoire 426 de la CGC.

Elkanah A. Babcock
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A LICHENOMETRIC STUDY OF HOLOCENE ROCK GLACIERS AND NEOGLACIAL MORAINES, FRANCES LAKE MAP AREA, SOUTHEASTERN YUKON TERRITORY AND NORTHWEST TERRITORIES

Abstract

Different ages of rock glaciers and Neoglacial moraines in southeast Yukon are readily differentiated on the basis of the size structures of their Rhizocarpon *populations and per cent lichen cover. Most rock glaciers formed from talus during the middle Holocene but formation and flow continued thereafter. Perhaps conditions for formation were climatically enhanced at several times during the middle and late Holocene but the apparent climatic signal is weak and equivocal. With one exception, glacial advances date from the last four centuries. Moraines are of several ages but there is no clear correlation between glacial advances and formation of rock glacier lobes during the last four centuries. Climatic change that led to Neoglaciation triggered only minor, if any, rock glacierization of talus, and whatever conditions led to massive rock glacierization of talus during the middle Holocene failed to trigger glacier growth. Rock glacierization is probably self regulated and occurs at a threshold talus thickness and ice content. Thresholds likely vary with geotechnical properties of talus, particularly grain size, and are only slightly modulated climatically.*

Large Rhizocarpon *lichens increase their diameters at the same rate as small ones so the growth rate is constant following the initial "great period"; hence the fundamental premise of lichenometry is correct.* Rhizocarpon *communities show no symptoms of senescence at 5000 years of age so the genus is useful in lichenometry beyond that.*

Résumé

Des glaciers rocheux d'âges différents et des moraines néoglaciaires situés dans le sud-est du Yukon peuvent être facilement différenciés en se fondant sur les tailles des populations de Rhizocarpon *et le pourcentage de couverture lichénique. La plupart des glaciers rocheux se sont formés à partir de talus au cours de l'Holocène moyen mais leur formation et leur écoulement se sont poursuivis par la suite. Le climat a intensifié les conditions propices à leur formation à plusieurs reprises au cours de l'Holocène moyen et supérieur mais le signal climatique apparent est faible et équivoque. Sauf une exception, les avancées glaciaires ont eu lieu au cours des quatre derniers siècles. Les moraines sont d'âge multiple mais aucune corrélation nette ne peut être établie entre les avancées glaciaires et la formation de lobes de glaciers rocheux au cours des quatre derniers siècles. Le changement climatique à l'origine de la néoglaciation n'aurait provoqué la formation que de petits glaciers rocheux et, quelles que soient les conditions qui aient contribué à la formation de nombreux glaciers rocheux au cours de l'Holocène moyen, elles n'ont pas déclenchée une croissance des glaciers. La formation de glaciers rocheux est probablement un processus d'autorégulation et ne se produit qu'à un niveau seuil d'épaisseur de talus et de teneur en glace. Ces seuils varient probablement en fonction des propriétés géotechniques du talus, en particulier de la granulométrie des sédiments, et ils ne sont que légèrement modifiés par le climat.*

Comme le diamètre des gros lichens Rhizocarpon *augmente à la même vitesse que celui des petits* Rhizocarpons, *la vitesse de croissance est constante après la "grande période" initiale; par conséquent, la prémisse fondamentale de la lichénométrie est correcte. Les communautés de* Rhizocarpon *ne montrant aucun symptôme de sénescence à 5000 ans d'âge, elles sont donc utiles en lichénométrie au-delà de cet âge.*

SUMMARY

The Frances Lake map area contains about 1000 Holocene rock glaciers and 168 small cirque glaciers. Different ages of substrate on rock glaciers and Neoglacial moraines can be distinguished readily on the basis of differences in size structures of *Rhizocarpon* populations and more crudely on the simple basis of per cent lichen cover. Rock glaciers have a much wider range of ages than do Neoglacial moraines. Within these ranges are features of many ages and possibly there is a continuum of ages. Such groupings as occur in the data may indicate a climatic signal but sampling of more features is necessary to confirm this. There is no clear correlation of ages of rock glaciers and moraines that date from the same general interval. Furthermore, most rock glaciers are much older than the moraines.

The oldest rock glaciers of the Frances Lake map area are about 4500 years old. Rock glaciers continued to form thereafter but conditions for formation may have been enhanced at several times. Perhaps 90% of the rock glaciers formed more than 1200 years ago, many around 4500 years ago, but whatever conditions governed their formation, they were insufficient to cause accumulation and advance of cirque glaciers. The rock glaciers are predominantly "talus glaciers" (rock glacierized talus) although some "moraine glaciers" (rock glacierized ice cored moraines) occur as well. The fact that most rock glaciers date from the middle Holocene may indicate that by that time sufficiently thick talus had accumulated that enough perennial ground ice could be maintained to trigger plastic deformation of the frozen basal talus. Hence, no change in climate is necessarily implied. In areas of relatively fine grained talus where debris sheets are produced in many years, layers of compacted avalanche snow and debris are built up and flow off the talus slopes as ice-rich talus glaciers.

The climate change that led to Neoglaciation triggerred only minor, if any, rock glacierization of talus. Many, perhaps most, rock glaciers have treads that are more than 1200 years old (older than White River Ash) adjacent to the active talus toe. Hence, during the last 1200 years the rate of talus accretion exceeded the rate of rock glacier flow in many places (the inner rock glacier treads are buried by talus). Possibly talus accretion rates have increased during Neoglaciation.

The *Rhizocarpon* data represent the size structures of communities that range in age from about 50 years to about 4500 years. All communities have positively skewed size structures and 4500 year old communities show no tendency toward senescence. Unoccupied substrate is always available for colonization and growth of young lichens. The diameter of the largest lichens in a

SOMMAIRE

La région représentée par la carte de Frances Lake renferme environ 1 000 glaciers rocheux et 168 petits glaciers de cirque datant de l'Holocène. On peut facilement distinguer sur les glaciers rocheux et les moraines n/oglaciaires des substrats de différents âges en fonction de la dimension des communautés de *Rhizocarpon* ou, de façon plus sommaire, simplement en fonction du pourcentage de terrain recouvert de lichen. L'âge des glaciers rocheux varie beaucoup plus que celui des moraines néoglaciaires. On a relevé un grand nombre d'âges différents et il pourrait en fait y avoir un continuum d'âges. Les regroupements notés dans les données pourraient être le reflet d'un signal climatique, mais il faudra échantillonner un plus grand nombre d'entités pour confirmer cette tendance. Il n'y a pas de corrélation évidente entre les âges évalués dans le cas des glaciers rocheux et des moraines qui datent de la même période. De plus, la plupart des glaciers rocheux sont beaucoup plus vieux que les moraines.

Les plus anciens glaciers rocheux présents dans la région illustrée sur la carte de Frances Lake datent d'environ 4 500 ans. Des glaciers rocheux ont continué à se former par la suite, mais il se peut que les conditions soient devenues plus propices à la formation de ces glaciers à plusieurs occasions. On croit que peut-être 90 % des glaciers rocheux se sont formés il y a plus de 1 200 ans et, en particulier, qu'un grand nombre de glaciers se sont formés il y a environ 4 500 ans : toutefois, pour autant qu'elles aient favorisé la formation de ces glaciers, les conditions qui prévalaient alors n'ont pas suffi pour que des glaciers de cirque s'accumulent et avancent. Les glaciers rocheux sont surtout des "glaciers d'éboulis" (talus d'éboulis devenus des glaciers rocheux), bien qu'on retrouve aussi un certain nombre de "glaciers de moraine" (glaciers rocheux qui au départ étaient des moraines à noyau de glace). Le fait que la plupart des glaciers rocheux datent du milieu de l'Holocène pourrait signifier que, à ce moment-là, les talus d'éboulis avaient atteint une épaisseur assez grande pour permettre l'accumulation d'une certaine quantité de glace permanente dans le sol, quantité suffisante pour provoquer une déformation plastique du talus de fond gelé. Ainsi, un changement du climat n'entre pas nécessairement en cause. Dans les régions de talus à grain relativement fin où il faut de nombreuses années pour produire des nappes de débris, des couches de neige d'avalanche et de débris tassés s'accumulent et s'écoulent des pentes d'éboulis sous forme de glaciers d'éboulis riches en glace.

Le changement climatique à l'origine de la néoglaciation n'a provoqué que très peu, sinon pas du tout, la transformation de talus d'éboulis en glaciers rocheux. On remarque dans bon nombre, sinon tous, les glaciers rocheux la présence d'une marche horizontale qui est adjacente au front d'éboulement actif et date de plus de 1 200 ans (c'est-à-dire plus ancienne que les cendres de White River). Ainsi, au cours des 1 200 dernières années, le taux d'accumulation du talus d'éboulis a dépassé le taux d'écoulement du glacier rocheux en de nombreux endroits (les marches internes du glacier rocheux sont recouvertes par des talus d'éboulis). Les taux d'accumulation des talus d'éboulis ont peut-être augmenté pendant la néoglaciation.

Les données sur les *Rhizocarpon* donnent la répartition des dimensions de communautés dont l'âge varie de 50 à 4 500 ans environ. Dans tous les cas, la répartition des dimensions est désaxée vers la droite et les communautés vieilles de 4 500 ans ne montrent aucun signe de sénescence. Il existe toujours des surfaces non recouvertes que les communautés peuvent coloniser et où les jeunes lichens peuvent croître. Le diamètre des plus grands lichens d'une

community varies linearly with respect to the diameter of the median lichen. Hence the largest *Rhizocarpon* increases its diameters at the same rate as smaller ones, that is, the growth rate is constant. Because there are no indications of senescence in communities as old as 4500 years, the lichenometric technique using *Rhizocarpon* should continue to work in discriminating ages of still older deposits.

Lecidea subsoridiza and *Sporastatia testudinea* are common lichens on younger deposits. *Sporastatia* attains its maximum size of 26 to 28 mm on deposits that are only 100 to 200 years old. Thereafter, increase in maximum size is arrested but the median size of *Sporastatia* communities continues to increase, which is a tendency toward senescence; hence the species is of limited use in lichenometry. *Lecidea subsoridiza* appears to have a linear growth rate for at least 300 years so the species is useful in lichenometry for a longer period.

communauté varie de façon linéaire en fonction du diamètre du lichen médian. On conclut ainsi que les plus grands *Rhizocarpon* augmentent en diamètre à la même vitesse que les plus petits, c'est-à-dire que le taux de croissance est constant. Parce qu'on n'a décelé aucun signe de sénescence chez des communautés dont l'âge atteint même 4 500 ans, on devrait pouvoir utiliser la technique lichénométrique fondée sur les *Rhizocarpon* pour déterminer l'âge de dépôts encore plus anciens.

Les lichens *Lecidea subsoridiza* et *Sporastatia testudinea* sont très répandus sur les dépôts plus récents. *Sporastatia* atteint une taille maximale de 26 à 28 mm sur des dépôts qui n'ont que 100 à 200 ans. Par la suite, les lichens qui ont atteint leur taille maximale cessent de croître, mais la taille médiane des communautés de *Sporastatia* continue d'augmenter, ce qui constitue un signe de sénescence. Par conséquent, l'utilité de cette espèce en lichénométrie est limitée. Le taux de croissance de *Lecidea subsoridiza* semble linéaire pour 300 ans au moins; ainsi, cette espèce peut servir pour une plus longue période aux fins d'études de lichénométrie.

INTRODUCTION

The Frances Lake map area (105 H) of the northeastern Canadian Cordillera is crossed by northwest-southeast trending ranges of the Selwyn Mountains. Treeline coincides approximately with the 1500 m contour and highest peaks are generally between 2100 m and 2450 m. The mountain ranges are heavily fretted and the cirques and other high alpine valleys contain 168 glaciers and approximately 1000 rock glaciers. Rock glaciers are common throughout the alpine zone (i.e., above treeline), whereas ice glaciers are nearly restricted to the higher northeast quarter of the map area and are confined to cirques with northerly aspect and with floors at about 1900 m or higher. The largest glacier is 3.3 km long and the largest rock glacier is 2.4 km long. Most rock glaciers appear to be of the "talus glacier" variety. None in the area are demonstrably of the "rubble covered glacier" variety; although some of those emanating from cirque heads could be of this type, most are believed to be talus glaciers. One example of rock-glacierized ice-cored moraine was encountered.

Rock glaciers occur widely throughout the alpine zone of Yukon Territory and District of Mackenzie and are much more widespread than glaciers (Vernon and Hughes, 1966; Hughes, 1972, 1983; Rampton, 1980a-d; Rampton and Paradis, 1981; Thomas and Rampton, 1982a,b; Jackson, 1986, 1987). In this respect the Frances Lake map area may be typical, or at least typical of the eastern ranges.

During the McConnell Glaciation (Late Wisconsinan) the Frances Lake map area was inundated entirely by south-flowing ice from a dispersal area of the Cordilleran Ice Sheet located in the Logan Mountains, a division of the Selwyn Mountains, just north of the area (Jackson, 1987; Dyke, in press, a). A multitude of recessional moraines, lateral and sublateral meltwater channels, crevasse fillings, and kames reveals the details of ice retreat, which involved a generally northward recession of the margin in the low valleys toward the main dispersal area as well as a retreat to several local centres of late ice within the map area, primarily to the presently glacierized massifs. Although no dates have been obtained on the timing of this ice retreat, it is presumed to have been completed by the earliest Holocene. During the Holocene extensive talus slopes formed and gave rise to talus glaciers and the cirque glaciers advanced to form fresh looking, mostly unvegetated moraine sequences. The youngest moraines have been abandoned during historical time. Most if not all glaciers are presently in a state of retreat. Substantial retreat has occurred since airphoto coverage was obtained in 1950.

Rock glaciers and neoglacial moraines were mapped during general surficial geological mapping in 1981 (Dyke, 1983; in press, a-e) and selected features were studied in detail in 1983 from six fly camps in the northeastern part of the study area. Cursory examination during the first field season revealed that rock glaciers and end moraines were each of several ages. The more detailed work during the second field season addressed the question of the importance of climate in rock glacier formation (does rock glacier formation correlate with moraine formation?) and assessed the physical properties of rock glacier development and flow. Hence, the intent was to address the research priorities outlined by Johnson (1973, p. 90), namely: "(1) History of rock glaciers individually and regionally. (2) Aspects of the morphology of rock glaciers. (3) Physical processes responsible for the origin and control of rock glacier development." Johnson elaborated: "The role of climate should... be fully examined and its relation to the formation and reactivation of rock glaciers be determined. So far little has been done in this regard except to indicate that some relation exists between the distribution of rock glaciers, treelines and glacial limits." The ages of rock glaciers and moraines were assessed through lichenometry, the only dating technique that can be applied to nearly all substrates. Lichenometric and some geomorphic data are reported here. Detailed instrument surveys of rock glacier morphology, installation of arrays of precisely surveyed pins to measure long term movement of 25 features, and mechanical analyses of rock glacier debris will be reported separately.

Lichenometric ages are thought to pertain to time elapsed since stabilization of substrate. This corresponds roughly to time elapsed since deposition of moraines and since initial flow of a rock glacier lobe or tread off from its parent apron. This report discusses the lichenometric method used and presents the results from the six study areas as well as a regional summary and correlation.

LICHENOMETRIC METHOD

Numerous lichenometric methods have been used to determine either relative or absolute ages of various Holocene deposits (Locke et al., 1979). Following their summary of the method, Locke et al. recommended that researchers employ size-frequency analysis of the population of a particular suitable species or genus on a given deposit, rather than simply recording the largest individual, in order to circumvent the problem that the largest individual(s) may not belong to the same population as the majority of lichens of that same species on the deposit. This situation arises, for example, when a block supporting one or more sizable lichen thalli lands on a rock glacier and the lichens survive and continue to grow on the rock glacier. By using size-frequency analysis, such anomalously large individuals are identified readily and removed from the sample and some other statistic (other than maximum size) can be used as a measure of relative or absolute age. Locke et al. suggested that the size-frequency analyses be based on samples of 1000 measurements and that the "1 in 1000 lichen" be used as the measure of maximum thallus diameter. Most studies in lichenometry use only the diameters of circular or nearly circular isolated individuals. However, Locke et al. suggested that in the case of size-frequency analysis, irregularly shaped masses of lichen could be used and that the diameter of the largest inscribed circle that could be accommodated within the irregular mass be recorded.

It was my intention to follow the method of Locke et al. in this study; however, it quickly became apparent that irregular masses of lichen of a single apparent species or genus almost invariably consisted of multiple coalescent individuals and that on older substrates, where such agglomerations are large and common, the largest inscribed circle probably would seriously overmeasure the size of any individual within the agglomeration. Therefore, a variation of the technique was adopted whereby only circular thalli were measured. Because of this, especially on older substrates, where the majority of lichens are coalescent, the sample size had to be reduced. At each site an attempt was made to locate 400 circular or nearly circular individuals within an area of substrate judged to be of uniform age. However, at several sites that number was not found after searching the entire substrate. Sample size generally was not a problem on younger deposits where small, isolated, circular thalli are common.

Crustose lichens of three sharply contrasting colours were used in this study and voucher specimens were identified at the herbarium of the National Museums of Canada. The green (or greenish yellow) and black *Rhizocarpon* lichens were sampled on nearly all substrates. Of 27 voucher specimens identified, 15 were *R. geographicum*, 3 were *R. eupetraeoides*, 3 were *R. inarense*, and 6 were *Rhizocarpon* not identifiable to species level due to lack of spores. Hence, at least 3 Rhizocarpon species are included in the *Rhizocarpon* samples but this is probably the case in most lichenometric studies using this genus (Locke et al., 1979) and it does not appear to hamper the technique. On younger substrates, circular thalli of a distinctive lichen with a black hypothallus and brown aureoles are common; three voucher specimens were identified as *Sporastatia testudinea.* Another common circular lichen on younger substrates is a bright silver grey; of 5 voucher specimens submitted, 4 were identified as *Lecidea subsorediza* and the other as *Aspicilia cinereorufescens.* Either two different genera were included in samples of silver grey lichens or there was some confusion as to which individual on the voucher rock sample was to be identified. Conclusions in this report are based almost entirely on the *Rhizocarpon* data, which are presented in detail. Measurements of the other genera are presented only in summary form.

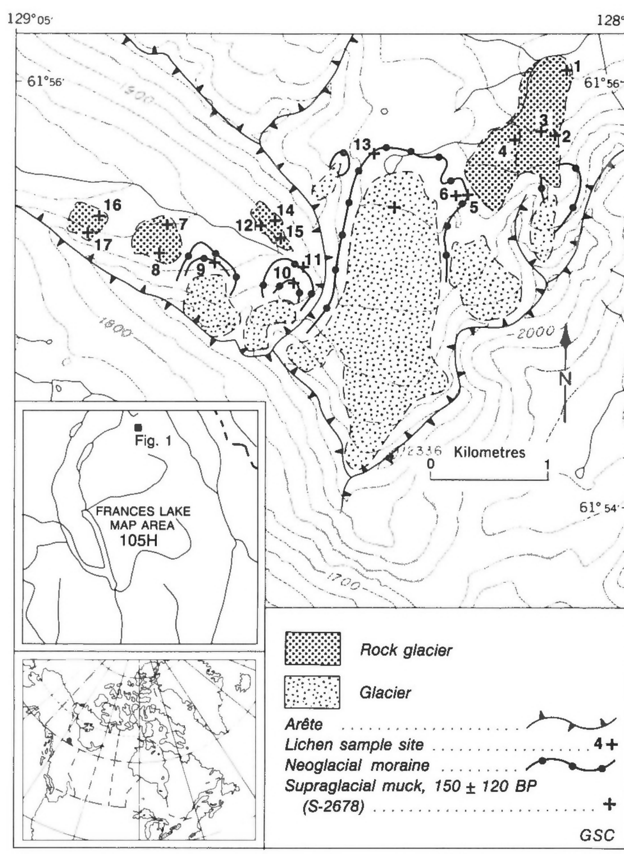


Figure 1. Sites studied in area 1.

Rhizocarpon appears to thrive on the variety of lithologies sampled - monzonite, gneiss, and phyllite. All study sites on both moraines and rock glaciers are topoclimatically similar and include the same variety of microenvironments. All sites are bouldery, well drained, and exposed to sunlight and wind. Large enough areas were searched at each site to ensure measurements from all types of microenvironments. Hence, if *Rhizocarpon* grows faster on southerly block faces, the chance that these fast growing individuals were included in the sample was the same at all sites.

RHIZOCARPON DATA AND GEOMORPHOLOGY

Area 1

Area 1 comprises the heads of two alpine valleys, both just above treeline; the valleys harbour six cirque glaciers and five rock glaciers. Lichen sizes were measured at 17 sites, 11 sites on rock glaciers and 6 on Neoglacial moraines (Fig. 1).

Rock glaciers

Two active coalescent rock glaciers with northerly aspect in the eastern valley have steep front and side slopes of nearly lichen-free blocks set in a loose, unstable, sandy, fine gravel matrix. The snout adjacent to site 1 holds an angle of 37°. The distal rock glacier tread is covered entirely by blocks of gneiss arranged in closely spaced, arcuate ridges and furrows that parallel the outline of the snout (Fig. 2A). Blocks at site 1 are as much as 4 m across, have a heavy crustose lichen cover, and have about 20% sod cover on and between blocks (Fig. 2B). Visual estimates of per cent crustose lichen cover on rock without sod cover indicate that most blocks have a 60 to 80% cover (Fig. 3A). Measurements of 400 circular thalli of Rhizocarpon within a 400 m^2 area at site 1 indicate that the population of such circular, noncoalescent individuals has a mode of 36 to 40 mm, a maximum of 180 mm, and that individuals in excess of 100 mm are rare (Fig. 4A). The lower half of this rock glacier appears to have a crustose lichen cover and largest *Rhizocarpon* sizes similar to those at site 1.

The upper half of the rock glacier has conspicuously less crustose lichen cover (Fig. 5) and a morphology different from that of the lower half. The upper half has two parallel, longitudinal sets of closely spaced, nested, transverse ridges, separated by a trench aligned along flow. Site 2, on the right hand set of ridges, has minimal lichen cover on blocks (Fig. 3B), whereas site 3, on the left hand set of ridges, has a lichen cover closer to, though still less than, that of site 1 (Fig. 3C). Measurements of 400 circular *Rhizocarpon* lichens at each of sites 2 and 3 indicate a different size structure of the populations at these sites. At site 2 individuals are most commonly 6 to 10 mm diameter and the largest individual is 27 mm (Fig. 4B). At site 3 individuals are most commonly 16 to 25 mm diameter and the largest individual is 75 mm (Fig. 4C). Hence, both the *Rhizocarpon* data and per cent lichen cover data indicate that three distinctly different ages of substrate occur on this rock glacier.

The tread of a small rock glacier that has coalesced with the rock glacier just described is covered with large blocks, commonly 4-5 m across. These have an extensive crustose lichen cover (Fig. 3D). Where matrix material appears at the surface in transverse ridges, sod cover is well developed and in places layers and lenses of White River Ash occur as partings in the soil Ah horizon (Fig. 6). White River Ash was deposited in this part of the Yukon about 1200 years ago (Hughes et al., 1972). The ash at site 4 rests on a 5 cm thick Ah horizon developed on the rock glacier rubble, so ash fall occurred after an interval of soil development that postdated formation of the rock glacier. The Ah horizon overlying the ash is only about 1 cm thick (Fig. 6). The size-frequency distribution of *Rhizocarpon* at site 4 is similar to that at site 1, although the somewhat greater abundance of circular thalli larger than 100 mm at site 4 possibly indicates a somewhat greater age (Fig. 4D).

Sites 7 and 8 are on the distal and proximal ends of the tread of a northeast facing rock glacier that has active front and side slopes and has a heavy lichen cover over most of its tread (Fig. 7A,B). The tread consists almost entirely of blocks of quartz monzonite with 0.5 to 4 m faces and lacks the transverse ridges and furrows typical of many rock glaciers. The distal tread (Fig. 1, site 7) has 60 to 70%

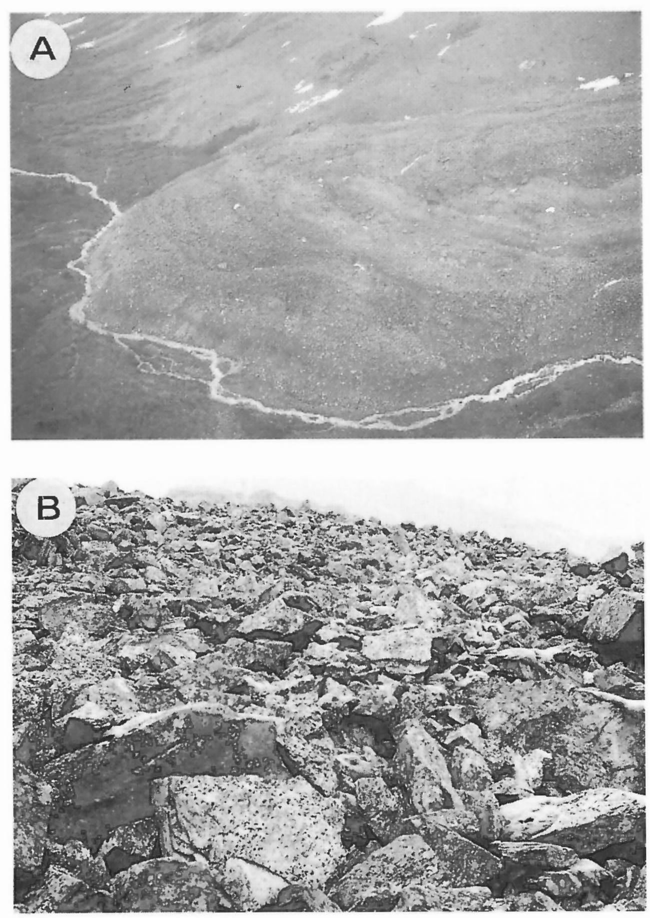


Figure 2. (A) Snout of rock glacier at site 1 and (B) ground view of lichen cover on blocky surface at site 1. 204511-L, 204510-P.

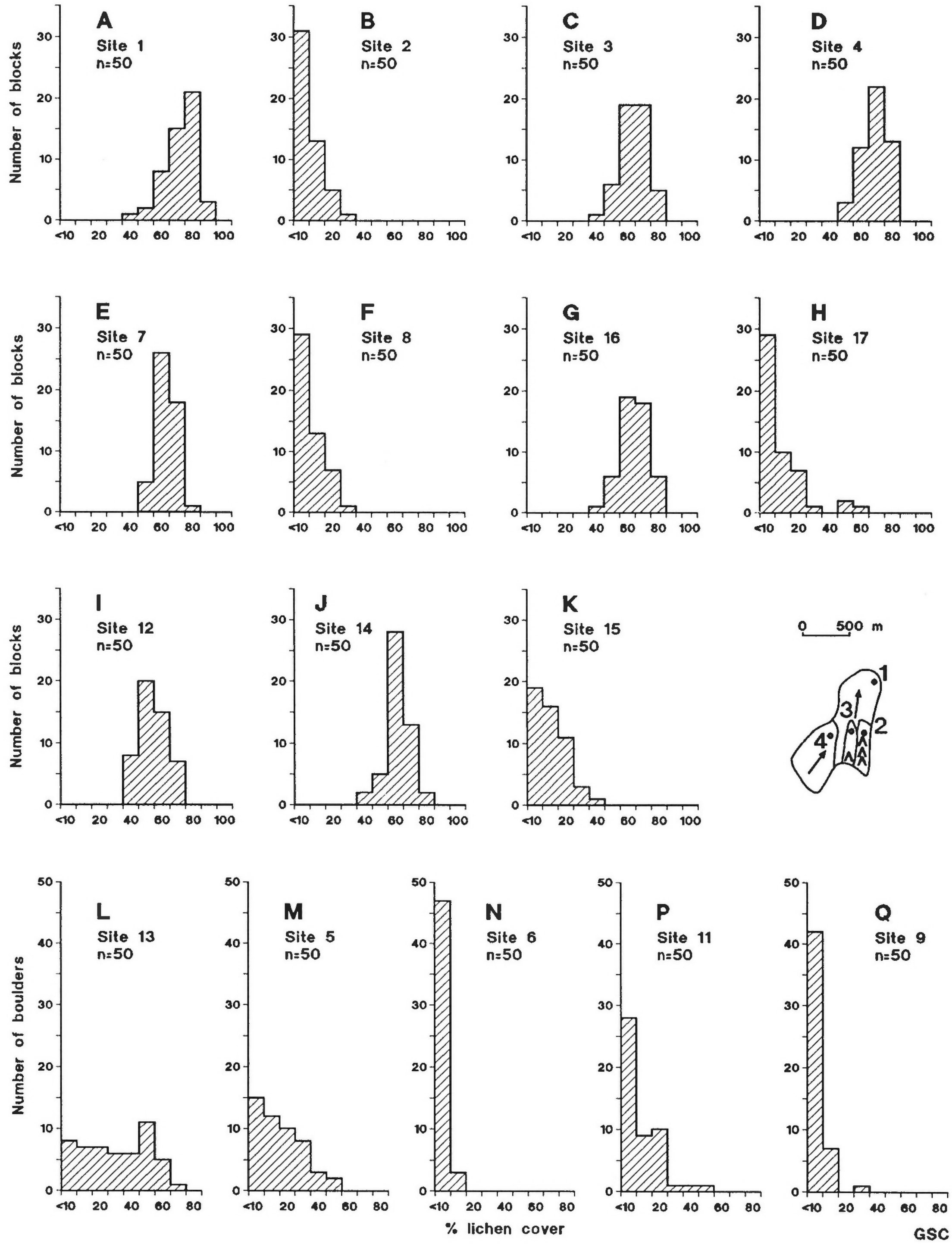


Figure 3. Histograms of per cent lichen cover on blocks at sites 1, 2, 3, 4, 7, 8, 16, 17, 12, 14, 15, 13, 5, 6, 9, and 11.

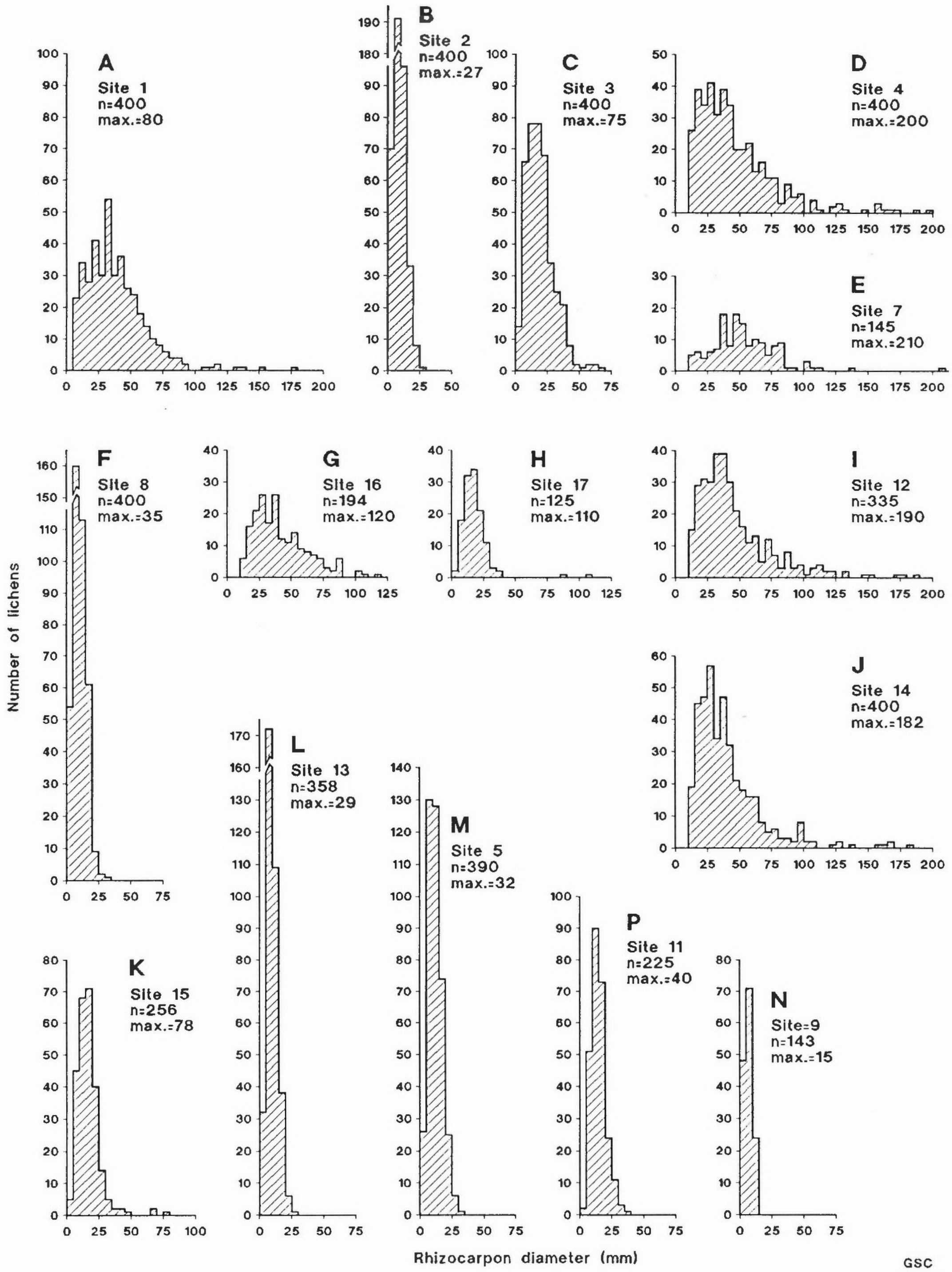


Figure 4. Histograms of *Rhizocarpon* diameters at sites 1, 2, 3, 4, 7, 8, 16, 17, 12, 14, 15, 13, 5, 6, 9, and 11.

Figure 5. Ground view of lichen cover on blocky surface at site 2. 204510-O.

Figure 6. White River Ash lens in soil at site 4. 204511-U.

Figure 7. (A) Down valley view of rock glacier at sites 7 and 8 and (B) ground view of lichen cover on blocky surface at site 7. 204510-M, 204510-L.

crustose lichen cover on most block faces (Fig. 3E, 7B). Circular thalli of *Rhizocarpon* are difficult to find here so only 145 were measured. Most commonly diameters are between 36 and 50 mm and individuals in excess of 100 mm are rare, though the largest encountered was 210 mm (Fig. 4E). The innermost part of the tread (Fig. 1, site 8) has minimal crustose lichen cover (Fig. 3F) and has a *Rhizocarpon* population dominated by juveniles, most commonly 6 to 10 mm and entirely less than 35 mm (Fig. 4F). This area is thought to lie in an area of lichen kill that resulted from expansion of snowbanks in the recent past, remnants of which still persist (Fig. 7A), rather than a younger age of rock glacier surface. However, incipient rock glacier lobes are forming on talus adjacent to site 8 and these lobes have lichen covers and *Rhizocarpon* sizes that appear to be closely similar to those sampled at site 8.

The other northeast facing rock glacier in the western valley (Fig. 1, sites 16 and 17) is morphologically and texturally similar to the feature just described (Fig. 8). Almost all of its block-covered tread has an extensive crustose lichen cover (Fig. 3G). But the innermost lobe, which protrudes about 100 m from an encroaching talus cone, is distinctly younger looking although a small proportion of blocks have a heavier lichen cover (Fig. 3H). Circular thalli of *Rhizocarpon* at site 16 are mostly less than 90 mm across and are most commonly 25 to 40 mm; the largest seen was 120 mm (Fig. 4G). *Rhizocarpon* lichens at site 17 are almost entirely less than 40 mm across. Individuals measuring 86 and 110 mm diameter occur on a single block with an extensive lichen cover (Fig. 4H).

The southwest facing rock glacier (Fig. 1, sites 12, 14, and 15) has several transverse and longitudinal block-covered ridges. Blocks on this feature are smaller than on other rock glaciers in this area, commonly only 10 to 30 cm across, and consist of gneiss and phyllite. Site 12 is on the outermost transverse ridge and site 14 is on a longitudinal ridge extending from a talus cone at the back of the feature up flow from site 12. Blocks at both sites have extensive crustose lichen covers (Fig. 3I,J). Site 15 is on a transverse ridge in front of active talus, the only part of the rock glacier that has a conspicuously lower lichen cover (Fig. 3K). Sites 12 and 14 have similar *Rhizocarpon* size structures with thalli common up to 100 mm or so and with maxima of 190 mm and 182 mm, respectively (Fig. 4I,J). Site 15 has a clearly younger

Figure 8. Down valley view of rock glacier at sites 16 and 17. 204510-N.

population of *Rhizocarpon* (Fig. 4K), in accordance with its lesser lichen cover (Fig. 3K) and position at the back of the rock glacier. Although the largest *Rhizocarpon* measured is 78 mm diameter, individuals larger than 50 mm are exceedingly rare.

Neoglacial moraines

All glaciers in the study area are fronted by Neoglacial till and all but one by distinct end and lateral moraines (Fig. 1); all glaciers face north. The moraine in front of the largest glacier is multicrested in places but is single crested elsewhere. At site 13 the moraine is single crested and sod covered. Boulders exhibit an unusually wide range of lichen cover, which yields a rectangular distribution not seen at other sites (Fig. 3L). Perhaps this unusual distribution indicates that some boulders are affected by cryoturbation and are constantly rotating and presenting fresh faces while others at the site remain more stable. Site 5, on the outermost crest of a multicrested segment of the moraine, is more boulder covered than site 13 and has a thinner sod cover; lichen cover at the site is less extensive but attains 50% (Fig. 3M). The outer several moraine ridges near site 5 have similar appearance, but at site 6 and farther up ice the moraines are sod-free and most boulders have little or no lichen cover (Fig. 3N). The *Rhizocarpon* populations at sites 13 and 5 are similar, with maxima of 29 and 32 mm, respectively, and modes at both sites of 6 to 10 mm (Fig. 4L,M), despite indications in the lichen cover data that the surfaces may be of different ages. At site 6 *Rhizocarpon* is abundant as specks 1 to 2 mm across; the largest seen was 5 mm, which indicates that the surface is distinctly younger than at sites 5 and 13.

About 100 m behind the 1983 position of the snout of the largest glacier are three conspicuous, ice-cored cones of black, foul-smelling, organic muck (Fig. 1). The muck cones are connected by a vein of ice containing disseminated black muck particles. This supraglacial and englacial muck could have been derived only from shearing up of subglacial organics, likely pond gyttja. The radiocarbon age of the muck, 150 $\pm$ 20 BP (S-2678), indicates that at some time during the past 1 to 3 centuries the glacier was much smaller than at present. The age of the muck provides a maximum date on the glacier advance that entrained it, but whether that advance culminated in construction of one or other of the terminal moraine ridges is not known. The 1983 glacier snout position is about 250 m behind the 1950 position and the glacier will retreat behind the muck cones again within the next 10 years or so if retreat continues unabated.

Two small cirque glaciers in the western valley have built moraines (Fig. 1, sites 9, 10, and 11). At site 10, on the inner of two moraine ridges, almost all boulders are completely lichen-free, and maximum lichen cover is about 5%. The outer moraine (site 11) has a more abundant, though still immature, lichen cover (Fig. 3P), whereas site 9 has a lesser lichen cover (Fig. 3Q). *Rhizocarpon* attains 40 mm diameter at site 11, with a mode of 11 to 15 mm; attains 15 mm diameter at site 9, with a mode of 6 to 10 mm; and is absent or of only minimal size at site 10 (Fig. 4N,P).

Summary

Different ages of both rock glaciers and Neoglagial moraines in Area 1 are reflected in conspicuously different extents of crustose lichen covers on blocks and boulders and in different size structures of *Rhizocarpon* populations. Transformation of the *Rhizocarpon* size-frequency data into cumulative curves plotted on a logarithmic scale results in a linear relationship and allows recognition of anomalously large individuals whose inclusion would seriously distort the shape of the curve. This in effect allows the exclusion of bogus maximum lichen sizes, ones not representative of substrate age, a serious but unassessable problem in lichenometric studies that rely only on maximum sizes. Locke et al. (1979) recommended that such individuals be excluded from the sample and that the curves be recalculated on the basis of the slightly reduced sample size. That recommendation is followed here. They further recommended fitting the data by a linear regression. But this assumes that all lichen populations have the same mathematical form, which is not necessarily the case, so here I present simple cumulative curves. Cumulative curves eliminate the effect of variable sample size, hence make comparisons between samples easier, and they offer the potential of assessing substrate age on the basis of population size structure, a proxy of age structure, rather than on the basis of a single statistic, such as the maximum lichen size.

Figure 9 presents cumulative curves showing percentage of *Rhizocarpon* with diameters larger than given sizes. Rock glacier substrates constitute two distinct groups. An older group has 1% of *Rhizocarpon* larger than 100 mm whereas a younger, more diffuse group has 1 percentile sizes of 21 to 62 mm. Neoglacial moraines and former snowbank sites have lichen populations similar to and younger than the younger rock glacier substrates. The cumulative curves suggest a possible continuum of ages of moraines and snowbank sites.

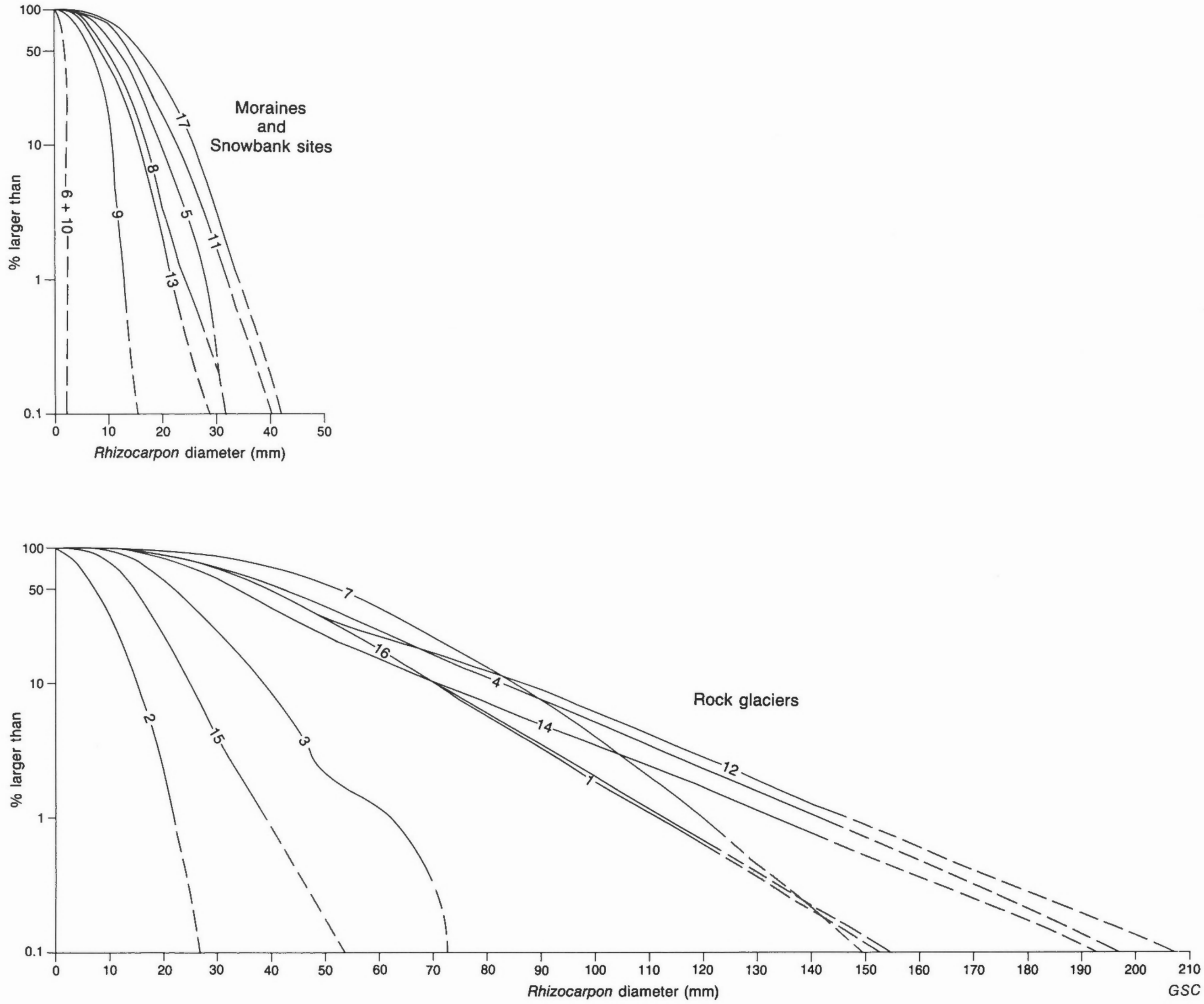


Figure 9. Cumulative curves of *Rhizocarpon* sizes on rock glaciers and Neoglacial moraines for sites in area 1.

Area 2

Area 2 comprises a north-south oriented alpine valley and west-facing tributary cirque valley (Fig. 10). These valleys contain 11 rock glaciers. *Rhizocarpon* lichens were measured at 10 sites, 2 on each of 5 features.

The west-facing rock glacier in the tributary cirque (Fig. 10, sites 18 and 19) has unstable, active front and side slopes and a tread almost entirely covered in blocks 1 to 6 m across (Fig. 11). Blocks consist of quartz-feldspar-mica gneiss. Most blocks are sound but about 10% exhibit cavernous weathering or surface granular distintegration. The entire tread has a mature crustose lichen community with 60 to 90% cover on most blocks (Fig. 12). The *Rhizocarpon* populations at both distal and proximal sites have closely similar size structures with modes of 36 to 40 mm, only rare individuals larger than 105 mm, and maxima of 140 mm (Fig. 13). At site 19, which is situated just in front of active talus, sod between the blocks contains 1 cm thick White River Ash lenses. Hence the entire rock glacier tread is more than 1200 years old and the net rate of flow of the rock glacier over the past 1200 years has not exceeded the rate of encroachment of talus material across the rock glacier tread.

The east-facing rock glacier at sites 20 and 21 (Fig. 10) sustains a steep overall slope and its snout extends below treeline and supports dense thickets of alpine fir growing in a *cladonia*-moss-heather understory (Fig. 14). The rock glacier has practically no side slopes, only a gentle slope at the snout, and has no active discharge of water, which possibly indicates that it is a relict feature. The lower tread has a mature lichen cover on blocks of gneiss (Fig. 12C) but the uppermost transverse lobe has a mixture of blocks with mature lichen cover and blocks recently fallen from the cliff above. Lichen cover on blocks at site 21, excluding blocks

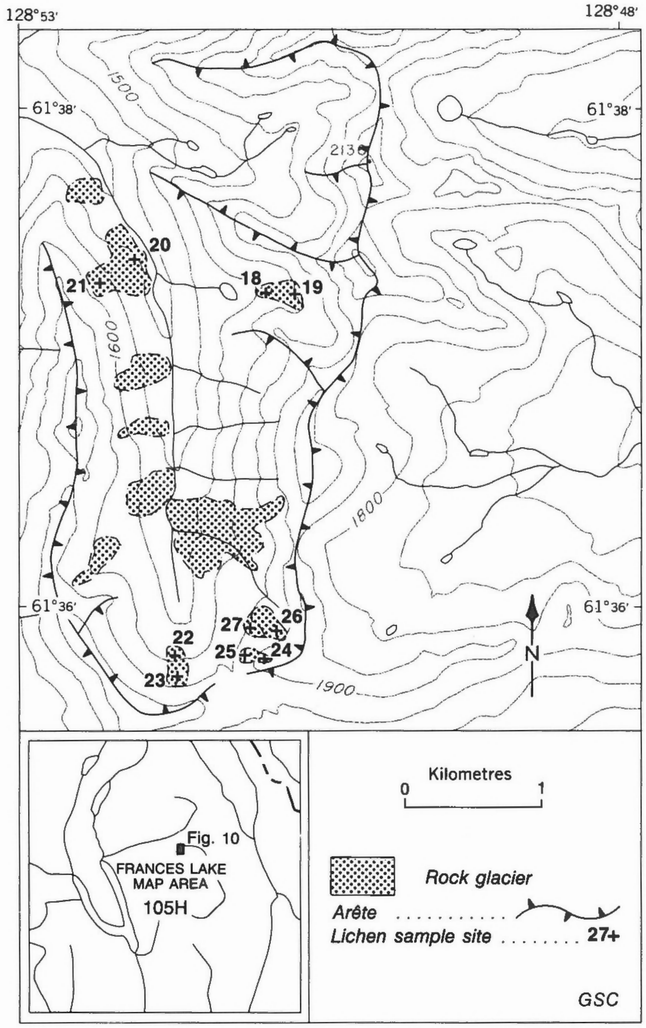


Figure 10. Sites studied in area 2.

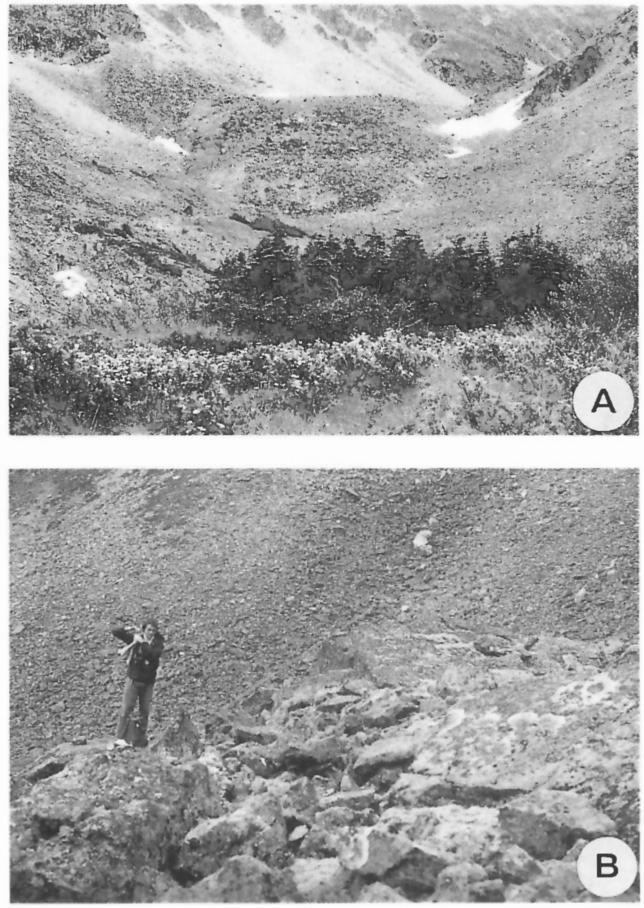


Figure 11. (A) Up valley view of rock glacier at sites 18 and 19 and (B) ground view of lichen cover on blocky surface at site 18. 204511-T, 204510-I.

that have obviously fallen onto the feature recently, is less than at site 20, but it is still possible that many of these blocks have fallen or rolled onto the feature (Fig. 12D). Circular *Rhizocarpon* lichens are exceedingly rare at both sites, likely due to the adverse effects of granular disintegration; only 101 individuals were located in a 2 hour search at site 20, 18 on a single large block, and only 37 in a 30 minute search at site 21. The largest individuals are 180 mm at site 20 and 93 mm at site 21, but the small sample size at site 21 makes it uncertain that there is a significant difference in age of substrate between the sites (Fig. 13C,D). A 2 cm thick White River Ash lens occurs beneath 20 cm of fibrous peat on top of a large block at site 20.

Sites 22 and 23 are at the snout and near the head of a north facing rock glacier (Fig. 15). Much of its front and side slopes are unstable and nearly free of lichens. Its tread has a 90% block cover of gneiss, monzonite, and marble. The marble sustains little or no crustose lichen cover but most of the rock glacier has a fairly extensive cover of crustose lichens on gneiss and monzonite blocks, similar to that at site 22 (Fig. 12E). The uppermost lobe is entirely free of lichens (Fig. 12G) and the lobe just below that, at site 23, has a minimal lichen cover (Fig. 12F). The size structures of the *Rhizocarpon* populations confirm that the substrates are of different ages at sites 22 and 23 (Fig. 13E,F).

Sites 24 and 25 are on the uppermost lobe and a lower lobe, respectively, of a small west facing rock glacier with a complete block cover mostly of quartz-feldspar-biotite gneiss. The more distal lobe has a markedly more extensive lichen cover than the uppermost lobe (Fig. 12H,I) and a higher frequency of larger *Rhizocarpon* lichens (Fig. 13G,H).

Site 26 is on the uppermost lobe of a small west facing rock glacier. Most of the rock glacier has a lichen cover typical of the oldest features seen in the area, has collapse pits, and appears relict, but the uppermost lobe has a somewhat reduced, though still extensive, lichen cover (Fig. 12J) which indicates a lesser age. *Rhizocarpon* sizes indicate a lesser age of substrate at site 26 (Fig. 13I) than at sites 18 and 19 (Fig. 13A,B) but a greater age than at sites 23 and 24 (Fig. 13F,H).

A small rock glacier abuts the rock glacier at site 27. Both its per cent lichen cover (Fig. 12K) and the size structure of its *Rhizocarpon* population (Fig. 13J) indicate that this feature is slightly younger than the feature at site 26.

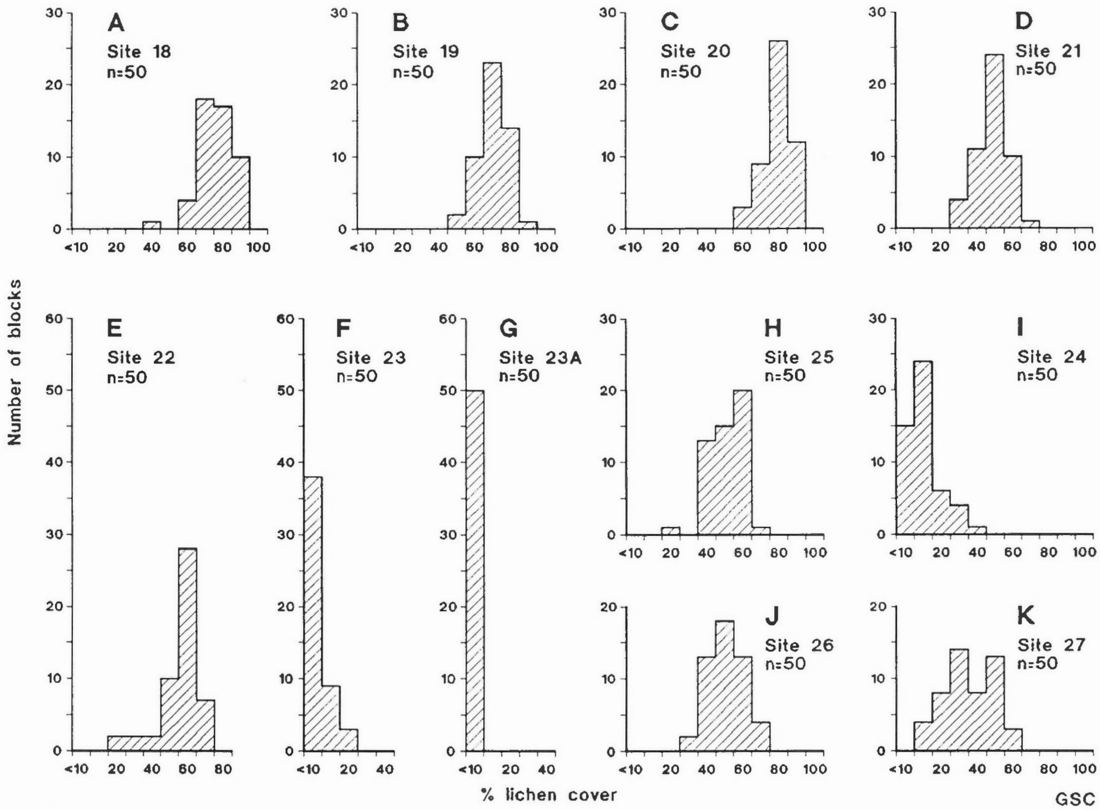


Figure 12. Histograms of per cent lichen cover on blocks at sites 18, 19, 20, 21, 22, 23, 24, 25, 26, and 27.

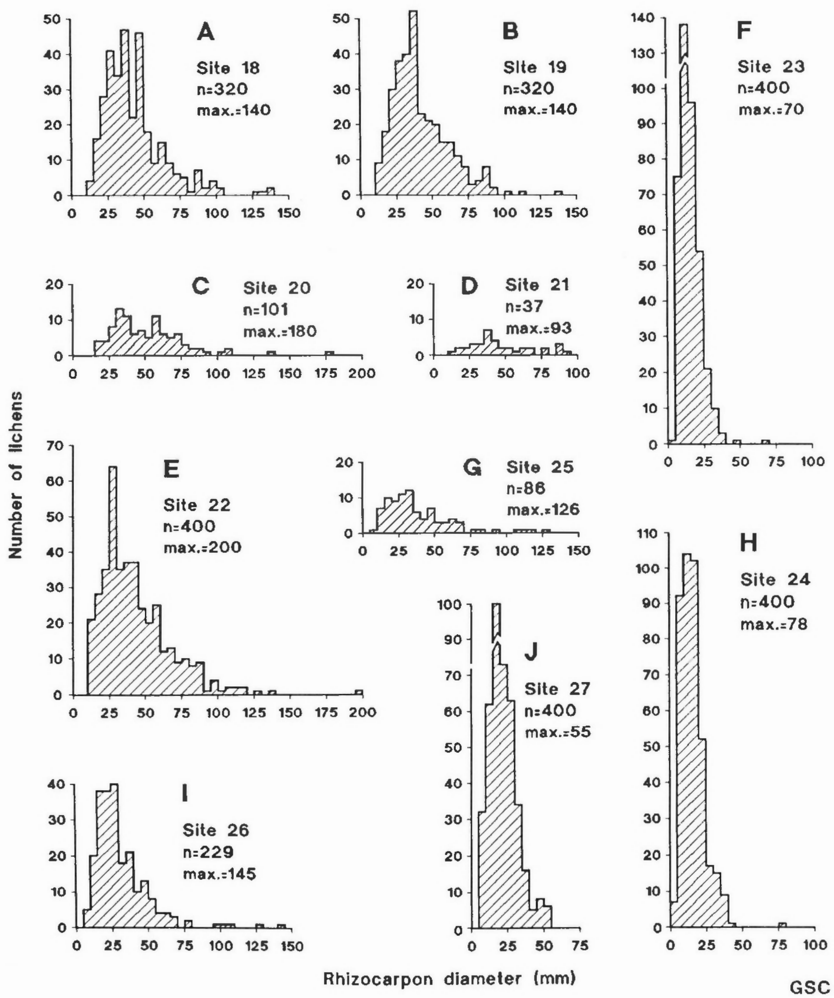


Figure 13. Histograms of *Rhizocarpon* diameters at sites 18, 19, 20, 21, 22, 23, 24, 25, 26, and 27.

Figure 14. Cross-valley view of stable, partly forested rock glacier snout at site 20. 204510-H.

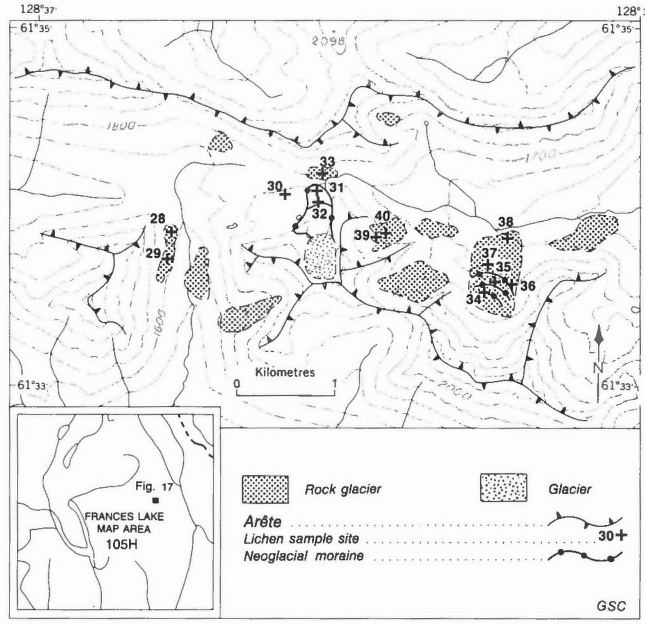


Figure 17. Sites studied in area 3.

Figure 15. Up valley view of rock glacier at sites 22 and 23. 204510-K.

Figure 18. Cross-valley view of two rock glaciers at sites 28 and 29. 204510-J.

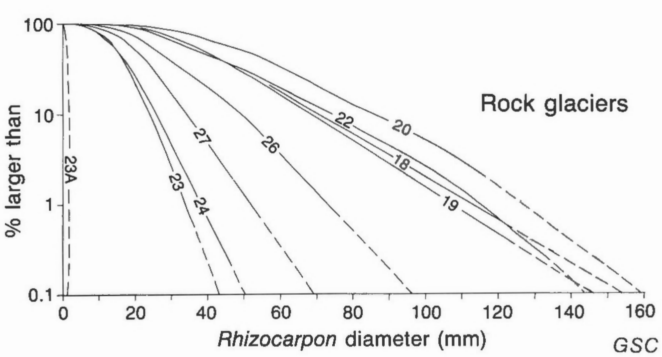


Figure 16. Cumulative curves of *Rhizocarpon* sizes on rock glaciers for sites in area 2.

Summary

Cumulative curves of *Rhizocarpon* sizes (Fig. 16) indicate the ages of rock glacier substrates sampled in area 2. Substrates at sites 18, 19, and 22, and perhaps 20 have closely similar ages and are clearly older than the other sites. In addition, the lobe above site 23 is free of lichens and represents the most recent phase of rock glacier activity in the area, represented by the dashed curve labelled 23A. As in area 1, rock glacier lobes that are younger than the oldest features have a range of relative ages rather than strong groupings.

Other rock glaciers in area 2 were examined in less detail. All parts of these features appear to have ages similar to ages of sites 18, 19, 20, and 22 because of their extensive crustose lichen cover and commonly large *Rhizocarpon* lichens.

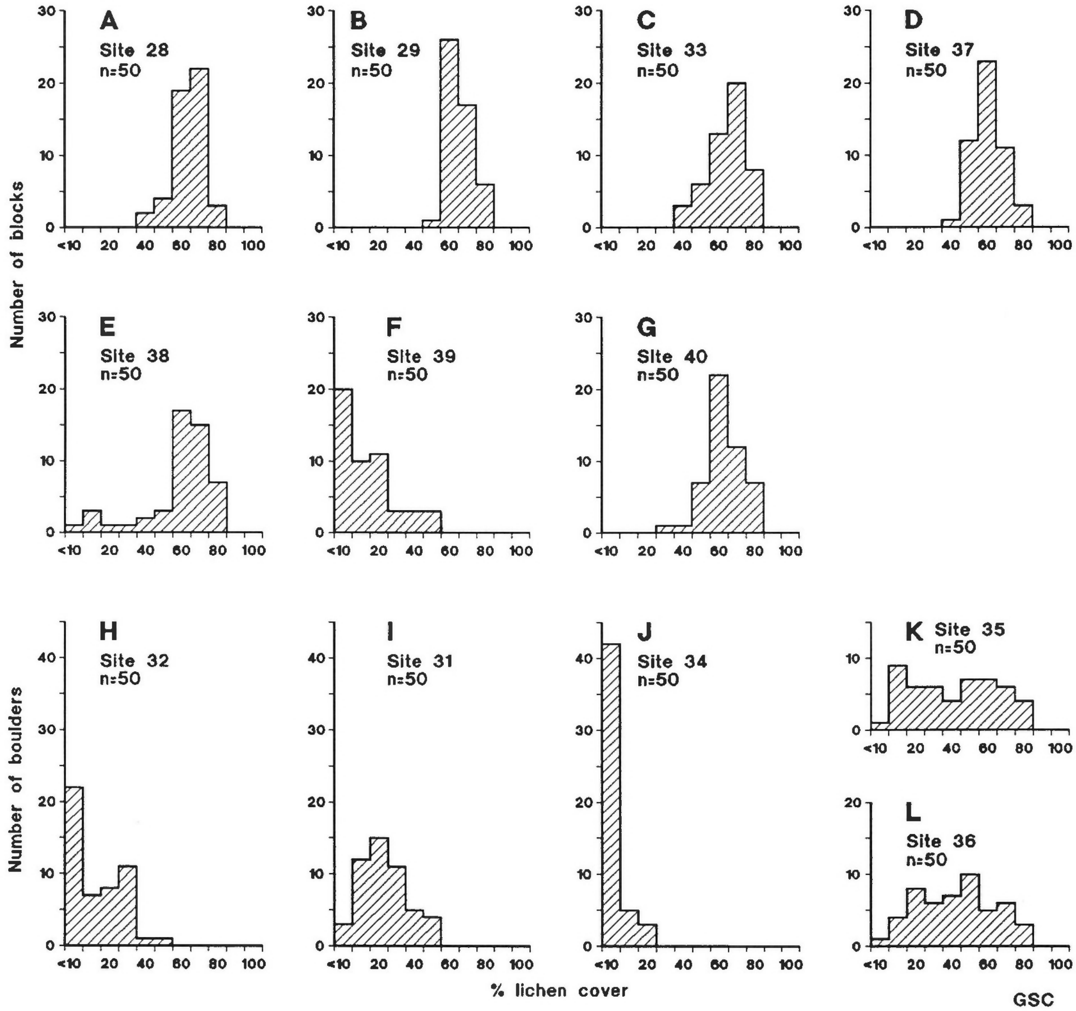


Figure 19. Histograms of per cent lichen cover on blocks at sites 28, 29, 33, 37, 38, 39, 40, 31, 32, 34, 35, and 36.

Area 3

Area 3 comprises two alpine valleys connected by a col (Fig. 17). *Rhizocarpon* sizes were measured on five rock glaciers, on Neoglacial moraines in front of two small glaciers, and in an area of lichen-kill by a former permanent snowbank.

Rock glaciers

Two laterally coalescent, east facing rock glaciers arise from the same talus apron on a slope west of the col (Fig. 17, sites 28 and 29). The rock glacier at site 28 has lichen-covered front and side slopes and appears inactive (Fig. 18). It has a simple tread with 100% cover of blocks, mostly monzonite. Parts of the tread have a mature crustose lichen cover (Fig. 19A) but much of it has only an immature lichen cover because of lichen kill by recent perennial snowbanks. Much of the talus abutting this rock glacier has a mature lichen cover. The rock glacier at site 29 has active side and front slopes and is backed by active, lichen-free talus (Fig. 18). Each talus cone gives rise to a longitudinal ridge on the rock glacier tread. The tread at site 29 is identical to that at site 28 in block cover and in block lithology and it exhibits a similar extent of lichen cover (Fig. 19B). The size structure of the *Rhizocarpon* populations is also similar at the two sites, although site 28 may be somewhat older, as indicated by the larger size of lichens in the modal class and by the greater abundance of lichens with diameters larger than 120 mm at that site (Fig. 20A,B).

A south facing rock glacier occupies the col between the two valleys (Fig. 17, site 33). Its surface is covered completely by monzonite and gneiss blocks, which are up to 8 m across, and has large collapse pits (Fig. 21). The pits are lighter toned because they harboured recent snowbanks that killed the crustose lichens. The western side of the rock glacier appears inactive. Blocks have a mature lichen cover (Fig. 19C) and the size structure of the *Rhizocarpon* population is typical of older rock glacier substrates (Fig. 20C).

The large rock glacier at sites 37 and 38 (Fig. 17) has been overrun partly by glacier ice and partly covered by till (Fig. 22). This rock glacier appears more active than most in the

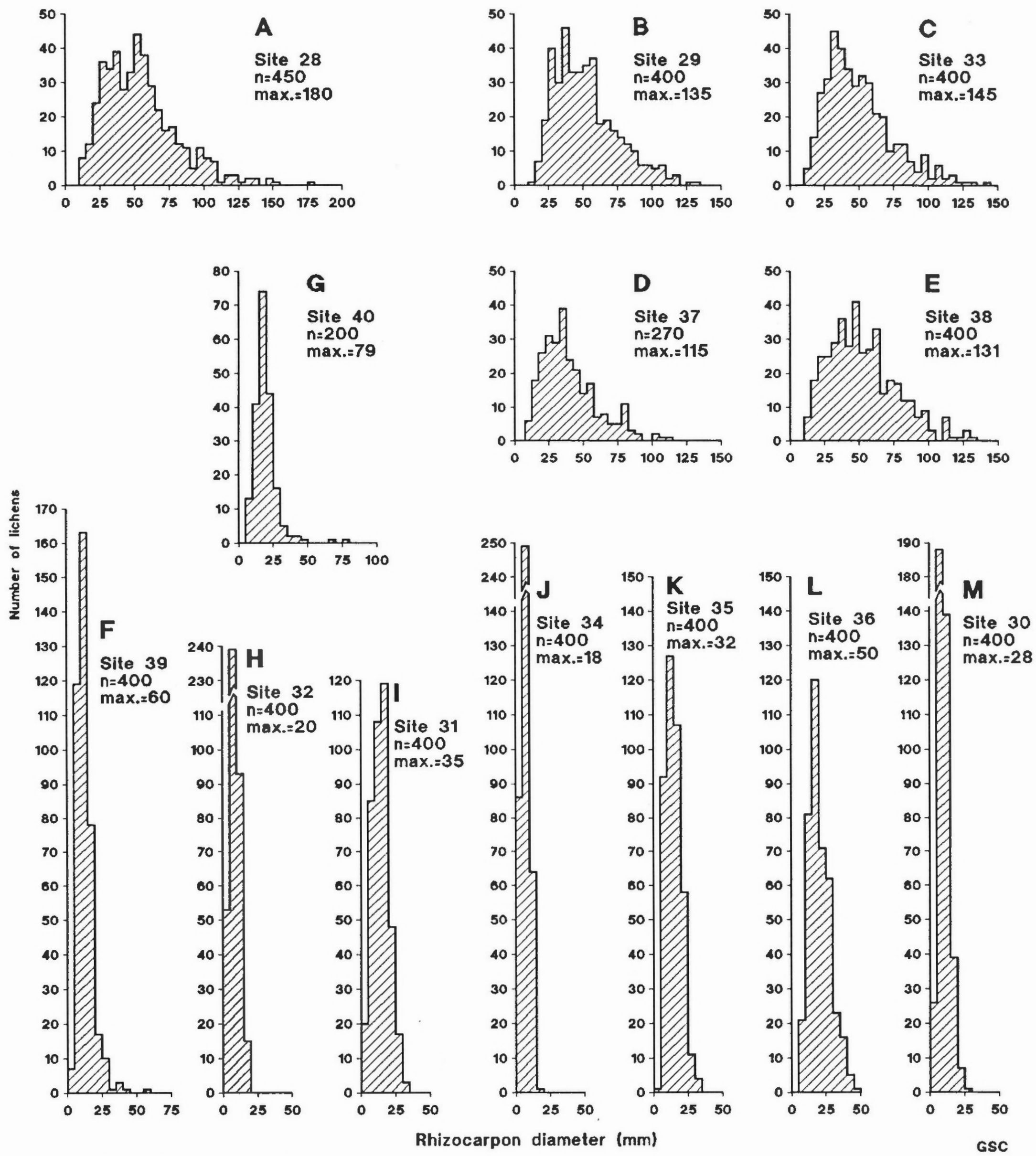


Figure 20. Histograms of *Rhizocarpon* diameters at sites 28, 29, 33, 37, 38, 39, 40, 31, 32, 34, 35, 36, and 30.

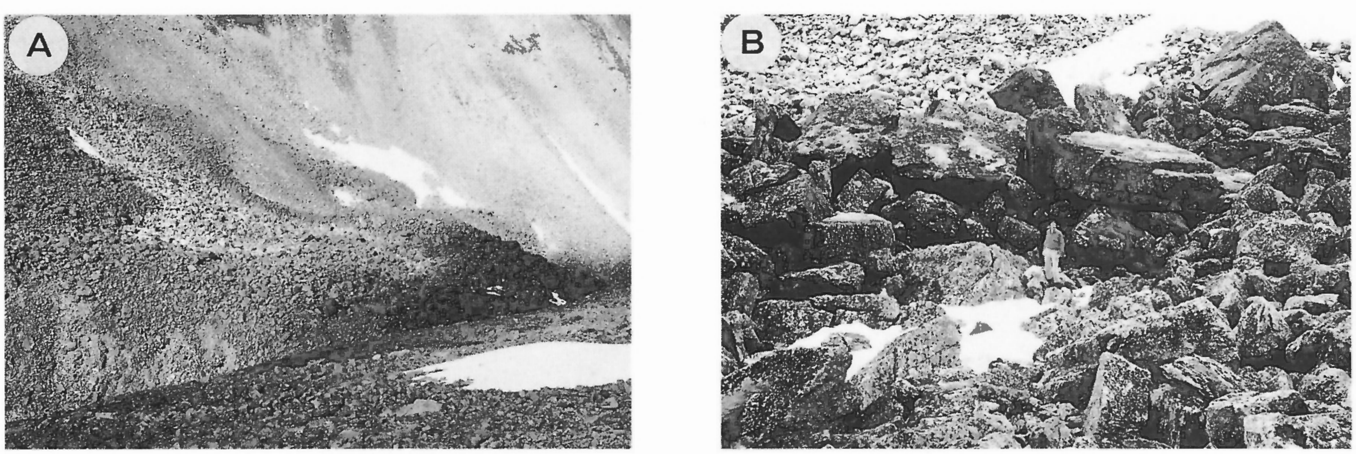


Figure 21. (A) Cross-valley and (B) close-up view of rock glacier at site 33. The light toned area in (A) is a collapse structure (depression) that harbours late lasting snow. The person and remnant snowbank in (B) are in a small collapse pit. 204510-E, 204511-S.

region with its oversteepened, very unstable side and front slopes; it is also one of the few which exhibits active discharge of water from its base. In places its snout has advanced across the main stream draining the valley. The tread is patterned by closely spaced transverse, arcuate ridges and furrows and is covered almost completely with blocks of monzonite. Although most blocks have a mature (60%) lichen cover (Fig. 19D,E), some are nearly lichen free, especially on the outer tread (Fig. 19E). These blocks with little lichen cover indicate overturning of blocks on the transverse ridges, a process that seems to be more active on the outer than on the inner part of the tread (Fig. 19D,E). Unvegetated matrix outcrops in the distal transverse ridges and indicates active shearing up of fine grained material. Hence the greater abundance of blocks with less lichen cover at site 38 (distal) than at site 37 (proximal) indicates a zonation of process within the rock glacier rather than a morphostratigraphic age reversal. If recently overturned blocks, with lichen covers of less than 50%, are ignored, site 38 would appear to be somewhat older than site 37, its proper age relationship, because of the greater abundance of blocks with 70 to 80% cover at site 38. This relationship is borne out by the size structure of the *Rhizocarpon* populations at the two sites; larger lichens are more common at site 38 and the mode occurs in a larger size class (Fig. 20D,E).

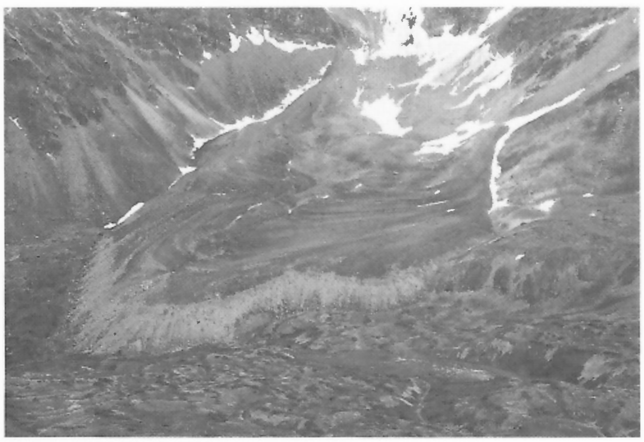


Figure 22. Cross-valley view of rock glacier at sites 37 and 38. Note the niche glacier at the cirque backwall and Neoglacial moraines overlying the inner rock glacier tread. 203603-V.

Figure 23. Cross-valley view of rock glacier at sites 39 and 40. 204510-G.

Sites 39 and 40 are on the youngest two lobes at the back of a bulky northeast facing rock glacier (Fig. 23). Today the back of the rock glacier is fringed by small perennial snowbanks but in the recent past the inner part of the tread was occupied by a small glacier that deposited lateral and end moraines. The uppermost lobes of this rock glacier are the only rock glacier features seen in area 3 that appear to be relatively young. The rest of the rock glacier tread has a lichen cover and *Rhizocarpon* sizes that appear typical of the older substrates, as at sites 28 or 29. The uppermost lobe extends about 20 m from the base of the active talus and has 100% cover of monzonite blocks, mostly 1 to 3 m across. These blocks have lichen covers that range from 0 to 50% (Fig. 19F); the blocks reflect a mixture of those that have been on the lobe for a while and those that have arrived recently by sliding across snowbanks from the active talus. Site 40, on the next lobe down flow, is similarly block covered but has a much more extensive lichen cover (Fig. 19G). The size structures of the *Rhizocarpon* populations at the two sites

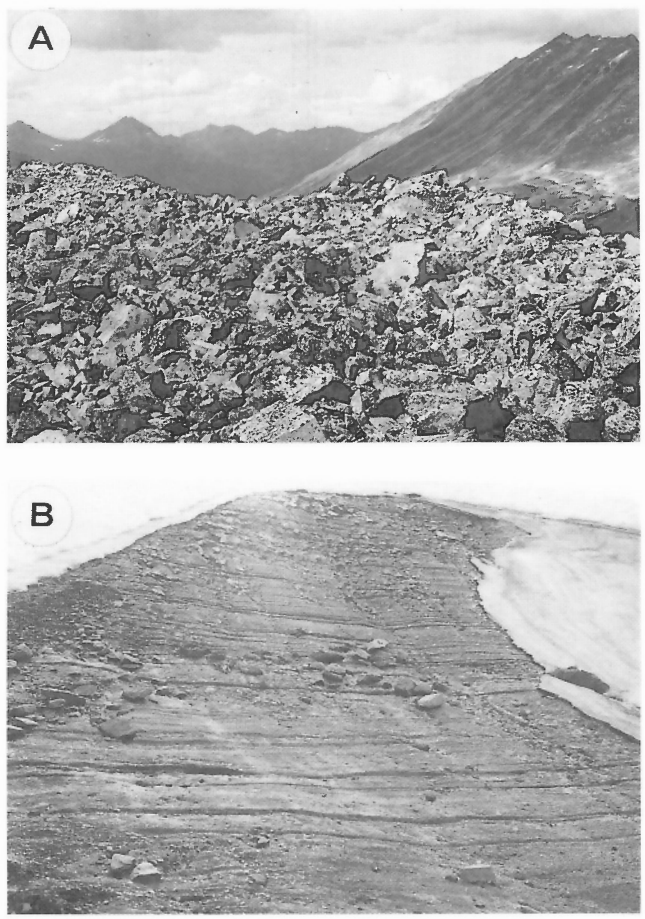


Figure 24. (A) Ground view of lichen cover on bouldery Neoglacial moraine at site 31. 204510-F. (B) Glacier ice with parallel debris bends exposed in stream cut through ice cored Neoglacial moraine at site 31. 204511.

are dissimilar in that the modal class occupies a larger size interval on the older lobe, but at both sites lichens larger than 50 mm are rare (Fig. 20F,G). On cursory examination, *Rhizocarpon* sizes on the small lateral and end moraines nearby appear similar to those measured at site 40.

Neoglacial moraines

Two unvegetated terminal moraines occur in front of the only extant glacier of area 3. The outer moraine at site 31 is about 15 m high, has a monzonite block-covered surface (Fig. 24A) and has a 10 m thick core of foliated glacier ice with debris bands (Fig. 24B). The inner moraine at site 32 is 2 to 4 m high, has monzonite block-covered crest and flanks, and snowbanks persist along its flanks (Fig. 25). Blocks on the outer moraine more commonly have a 10 to 50% lichen cover than do blocks on the inner moraine, where covers of less than 10% dominate (Fig. 19H,I). Blocks on the inner moraine exhibit highly variable lichen cover even in small areas because of varying stability. The size structures of the *Rhizocarpon* populations are distinctly different on the two moraines. Lichens up to 35 mm diameter are common on the older moraine but do not exceed 20 mm on the younger moraine, and the modal class shifts from 11 to 20 mm on the older to 6 to 10 mm on the younger (Fig. 20H,I). No moraines occur behind the ridge at site 32 but the bouldery till, which extends from the base of the end moraine to the active glacier snout, is entirely lichen free. Hence, the youngest end moraine has been available for colonization much longer than the till directly behind it. Lichenometric dates on end moraines usually are interpreted as relating to the time of moraine stabilization following initial ice retreat (Miller, 1973). However, here lichens clearly colonized the end moraine before the glacier retreated and exposed the adjacent till and the lichenmetric "date" applies closely to time of moraine construction rather than ice retreat.

Between construction of the youngest end moraine and 1983, the glacier retreated about 250 m. The configuration of the glacier on July 24, 1983 and the position of a cairn erected 15 m in front of the snout on that date are shown in Figure 26. The equilibrium line in 1983 was entirely above the glacier. The glacier had an S-shaped longitudinal profile and appeared thinner at the middle than at the head or snout; further thinning at the middle could isolate the lower glacier as a detached dead ice mass.

Figure 25. Ground view of lichen cover on bouldery Neoglacial moraine at site 32. 204510-X.

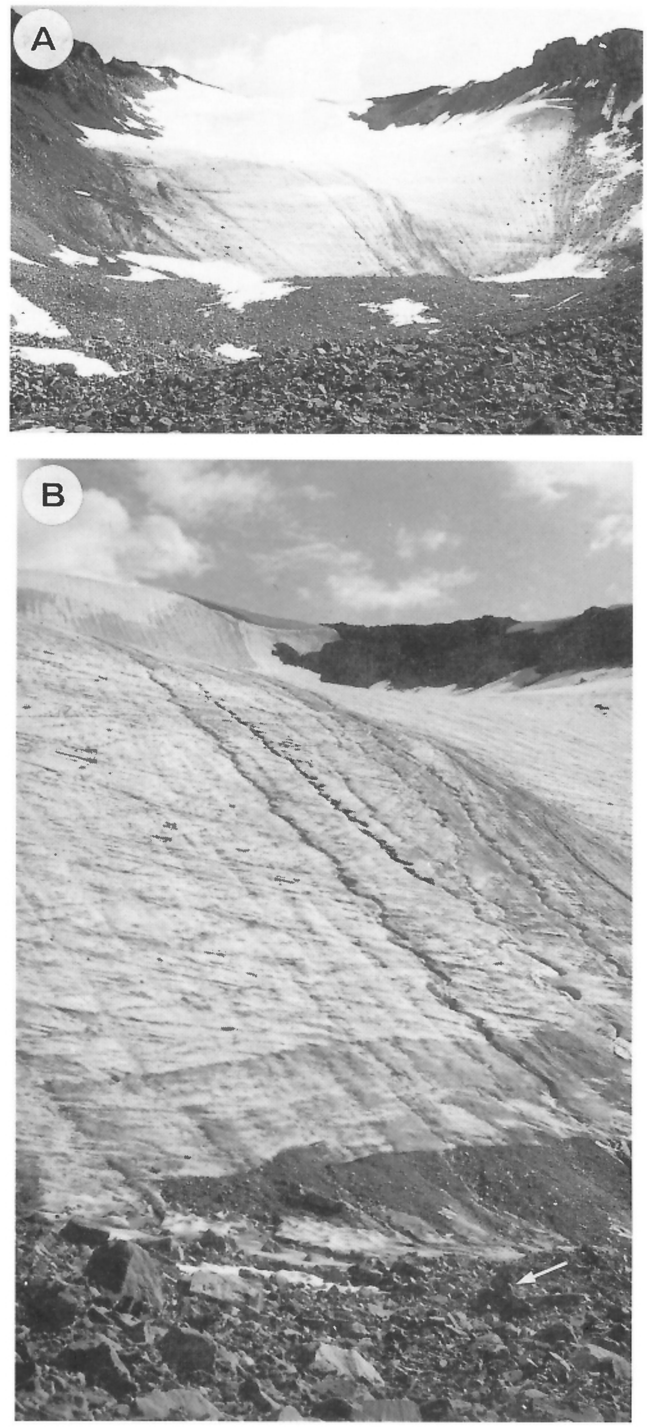


Figure 26. (A) Glacier behind site 32 and (B) cairn in front of glacier behind site 32, July 24, 1983. 204511-W, 204510-U.

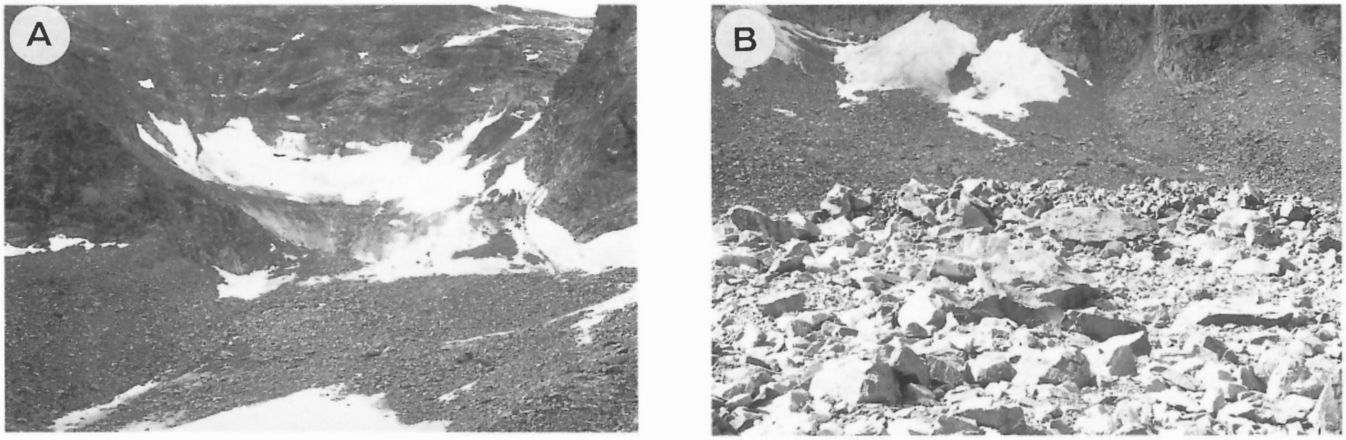


Figure 27. (A) Niche glacier behind site 34, July 26, 1983. 204510-V. (B) Ground view of moraine at site 34; a small cairn is marked by the arrow (see text). 204511-Q. (C) Ground view of distal slope of moraine at site 36. 204510-D.

Three nested end moraines overlie the inner half of a large rock glacier described above (Fig. 17, sites 37 and 38; Fig. 22). The glacier that formed these moraines had ablated almost entirely by 1950, but in 1983 a niche glacier still persisted as in 1950 (Fig. 27A). The moraines are steep sided, narrow crested, and covered with monzonite blocks. The innermost moraine at site 34 is unvegetated (Fig. 27B); the middle moraine, although composed almost entirely of blocks, has a thin sod and vascular plant cover on patches of till matrix material; and the outermost moraine (Fig. 27C) has a yet thicker sod cover and more extensive vascular plant cover. The innermost moraine has much less crustose lichen cover than the other moraines but the outer two moraines are not different from each other in this respect (Fig. 19J-L). However, each moraine has a distinctly different size structure to its *Rhizocarpon* population with both mode and maxima shifting systematically with relative age (Fig. 20J-L).

Figure 28. Ground view of snowbank lichen-kill area at site 30. 204510-Z.

Lichen-kill site

Several hectares of nearly lichen-free till occur on north-facing slopes in the col between the two valleys of area 3 (Fig. 28; Fig. 17, site 30). These resulted from killing and removal of crustose lichens by former perennial snowbanks, remnants of which still persist during the summer (Fig. 28). The chief geomorphic effect of the former snowbanks was the nearly complete removal of till matrix material which resulted in a surface boulder lag. Boulders near the centre of the lichen-kill zone lack *Rhizocarpon* and generally lack all other lichens as well, but lichen cover increases toward the edge of the lichen-kill area. This pattern could reflect the pattern of ablation of the former snowbank or the pattern of recolonization inward from the edges. The size structure of the *Rhizocarpon* population near the edge of the lichen-kill area suggests that the former snowbank shrank at a time intermediate between times of construction of the two terminal moraines by the adjacent glacier (cf. Fig. 20M and 20H,I).

Summary

Rock glaciers, Neoglacial moraines, and former snowbank lichen-kill areas of different ages occur in area 3 (Fig. 29). Rock glacier substrates at sites 28, 29, 33, and 38 have closely similar ages, and other unsampled rock glaciers in the area, on cursory inspection, also appear to be of similar age. Much younger rock glacier lobes, with immature crustose lichen covers, occur at the head of only one rock glacier (sites 39 and 40). Neoglacial moraines have a range of ages, but only one is apparently as old as the youngest rock glacier lobes. Moraines at sites 31 and 35 were deposited by different glaciers and are likely correlative. The interval of expanded perennial snowbanks ended between times of construction of moraines and before the latest Neoglacial advances.

Area 4

Area 4 contains 12 rock glaciers composed mostly of limestone debris (Fig. 30). In general, debris of this lithology does not support *Rhizocarpon* or other crustose lichen species that are common on acidic rocks, so lichenometric measurements were made at only one site (site 41) where some clasts of igneous rock occur on the headward part of a rock glacier. That tongue shaped rock glacier (Fig. 31) has a 30% sod cover supporting vascular plants near its snout. The sod apparently contains no White River Ash so the entire feature may be younger than 1200 years. At site 41, about 100 m down flow line from the head of the rock glacier, *Rhizocarpon* sizes indicate a relatively young surface, with a maximum size of only 31 mm (Fig. 32).

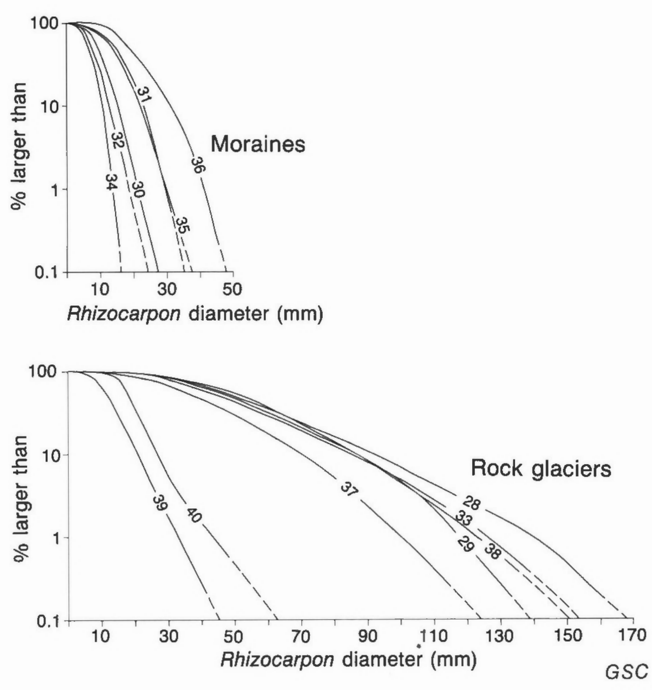


Figure 29. Cumulative curves of *Rhizocarpon* sizes on rock glaciers, Neoglacial moraines, and a snowbank lichen-kill site for sites in area 3.

General observations of other rock glaciers in area 4 bear on the question of age and origin of the features. Most features here actively discharge water during the summer. The lower reaches of many features are completely sod covered and support vascular plants, dwarf birch and willow,

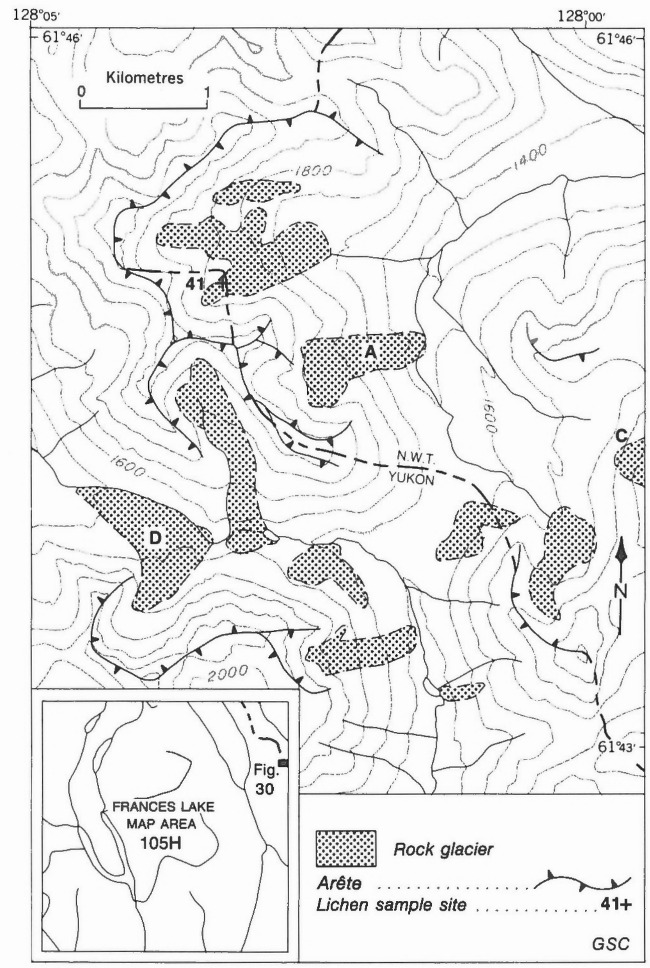


Figure 30. Sites studied in area 4.

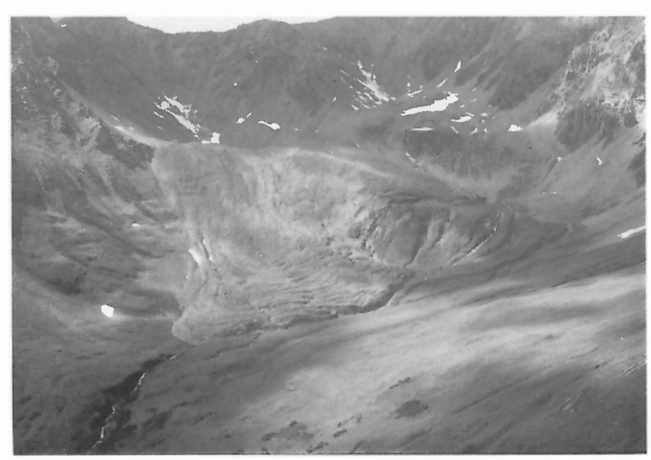
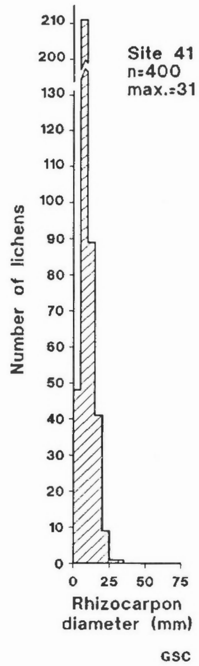


Figure 31. Cross-valley view of rock glacier at site 41. 204510-Y.

Figure 32. Histogram of Rhizocarpon diameters at site 41.



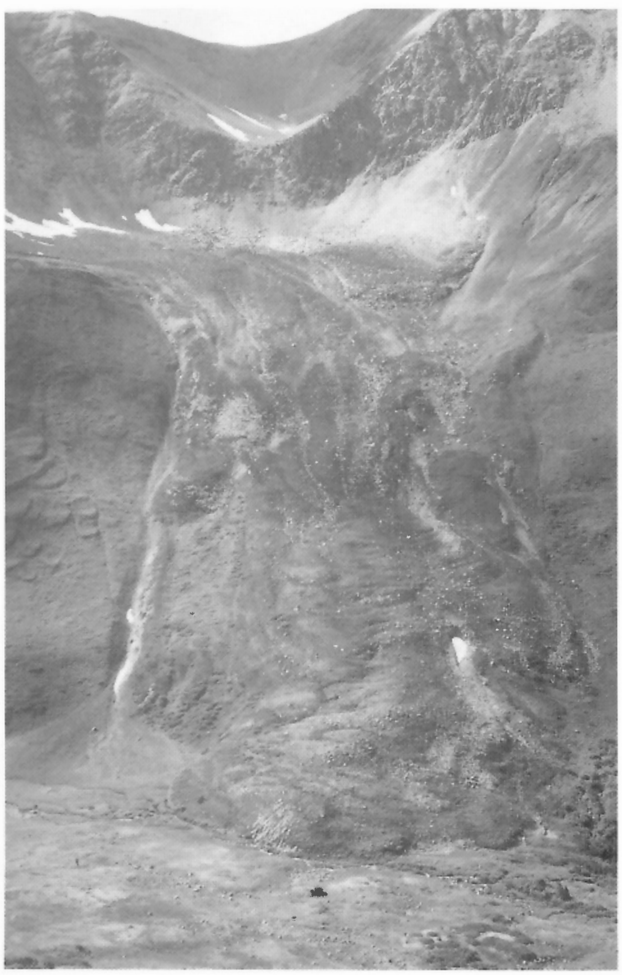


Figure 33. Cross-valley view of rock glacier A (Fig. 30). 204511-R.

and alpine fir, as exemplified by rock glacier A (Fig. 30, 33). Invariably White River Ash occurs in the sod at these sites. On rock glacier C (Fig. 30), White River ash can be traced back to a point about 100 m in front of the active talus toe. This probably represents the approximate distance the feature has flowed in the last 1200 years and suggests an average flow rate of 8.3 cm/year. Rock glacier C has a lesser slope than most features in this area so most features probably flow faster.

The heads of most rock glaciers and the abutting talus toes in area 4 have hummocky surfaces. These hummocky areas are underlain by interlayered rock fall debris and compact or metamorphosed avalanche snow, the snow being the thicker. These interlayered snow and debris sheets are laterally extensive in places (Fig. 34A,B; Fig. 30, site C) and when incorporated into the rock glaciers they produce massive ice with distinct parallel angular debris bands (Fig. 34C; Fig. 30, site D). In rock glacier D, which is deeply incised by a thermokarst stream, debris bands at the head of the rock glacier dip down glacier and are parallel to the surface of the upper rock glacier tread and lower talus toe; farther down flow the debris bands assume a shallow up-glacier dip and farther still a steeper up-glacier dip. The ice derived from the avalanche snow eventually resembles true glacier ice (originating from snowfall). It appears that incorporation of avalanche snow as layers or lenses between sheets of rock fall debris is an important process in generating rock glaciers where talus material is fine grained, as in area 4. The process is likely less important in areas of coarse grained talus as occurs in areas of monzonite and gneiss because it is unlikely that debris sheets are produced there annually on talus slopes.

Area 5

Area 5 comprises a northwest oriented alpine valley draining two presently glacierized cirques (Fig. 35). Lichenometric studies were done on three rock glaciers and on three Neoglacial moraines.

Rock glaciers

Two adjacent, though not coalescent, north facing rock glaciers (Fig. 36) and a south facing rock glacier were examined. Where not affected by lichen kill, the risers of the north facing rock glaciers are extensively covered by lichens and appear stable (Fig. 37). Both rock glaciers have well developed transverse ridges and furrows (Fig. 36).

The western feature is mantled by blocks of gneiss averaging 1 to 2 m and up to 6 m across. The head is nearly separated from the active talus by a depression, formerly occupied by a small glacier or large snowbank, or by interlayered ice and debris, and hence little debris currently enters the feature. The head and toe of the rock glacier both have mature crustose lichen covers (Fig. 38). *Rhizocarpon* populations at both head and toe have closely similar size structures (Fig. 39).

The other north facing rock glacier morphologically resembles the western one (Fig. 36). But unlike the western feature, it is mantled by blocks of phyllite and the head is not

Figure 34. (A) Upslope view of talus debris layer partly covering avalanche snow on cirque sidewall adjacent to rock glacier D. 203603-R. (B) Close-up view of talus debris layer partly covering avalanche snow on the cirque headwall talus at the top of rock glacier D. 204511-N. (C) Ice core with parallel angular debris bands, about 30 cm apart, exposed in a thermkarst stream cut through the centre of rock glacier D (Fig. 30). 204511-P.

isolated from its talus source. Furthermore, the extent of lichen cover on blocks varies from minimal at the top (site 47, not measured) to intermediate in the middle (Fig. 38B; Fig. 35, site 48) to mature at the toe (Fig. 38C; Fig. 35, site 49). This apparent relative age zonation is reflected in the size structure of the *Rhizocarpon* population (Fig. 39C-E). Between sites 48 and 49, sod on a large block contains a 5 cm thick lens of White River Ash so the substrate at site 49 is more than 1200 years old.

The south facing rock glacier is a much less bulky feature than the other two. It has flowed downslope and deformed a Neoglacial lateral moraine (Fig. 35, 40) which now functions as part of the rock glacier. Hence, the snout is composed of fine till-like material with only 10 to 20% block cover and with a thin sod cover. No White River Ash occurs in the sod. The feature is free of sod and vascular plants above the lowest three transverse ridges, that is, at site 51 and above. Phyllite blocks at sites 51 and 52 have minimal crustose lichen covers (Fig. 38D,E) and cover decreases to near zero at the very top (Fig. 38E, site 52). The *Rhizocarpon* population exhibits a systematic decrease in both maximal and modal sizes from toe to head (Fig. 38F-H). This rock glacier is unique among those examined. Its snout is younger than the snout of any other feature and it has a succession of still younger transverse ridges above the snout. Part of its snout, however, (Fig. 35, site A) has a mature lichen cover and has *Rhizocarpon* lichens in the size range of those on the two north facing rock glaciers (not measured).

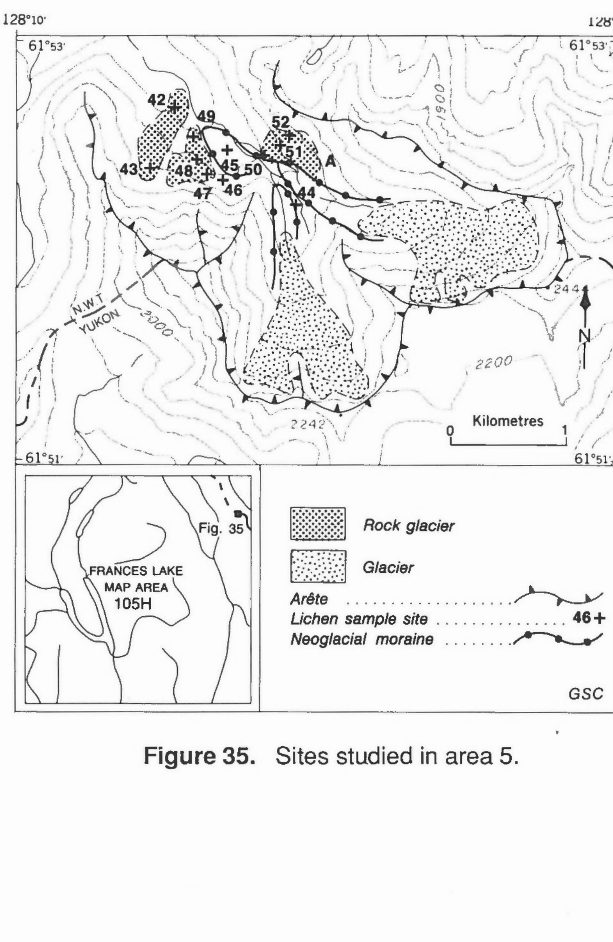


Figure 35. Sites studied in area 5.

Neoglacial moraines

During the Neoglacial the two large glaciers coalesced, expanded down valley, and deposited a massive, multiridged terminal moraine complex (Fig. 35, site 45). After separation of the glaciers during retreat, they paused or readvanced to build younger end moraines (site 44). Clasts in both sets of moraines are mostly phyllite. The younger moraine (site 44) has a flat crest, 20% boulder cover and a thin sod cover supporting scattered willow and vascular plants (Fig. 41). Crustose lichen cover is minimal (Fig. 38F) and *Rhizocarpon* occurs only as specks, the largest 5 mm diameter. The older moraine (Fig. 35, site 45) has a subdued morphology and has a better developed sod and vegetation than does the younger moraine (Fig. 42). It also has a much more extensive crustose lichen cover (Fig. 38G) and a conspicuously more mature *Rhizocarpon* population (Fig. 39I-K). A large sample of 1000 circular *Rhizocarpon* lichen was measured at this site to examine the effect of sample size on inferred population size structure. Subsamples of 400 gave aceptably reproducible results and a sample of 200 is probably adequate (Fig. 39I-K).

Figure 36. Down valley oblique aerial view of two north-facing rock glaciers of area 5. A small lateral moraine (arrow) occurs in the foreground. 204511-O.

Figure 37. Up valley ground view of stable snout of rock glacier at site 42. 204511-M.

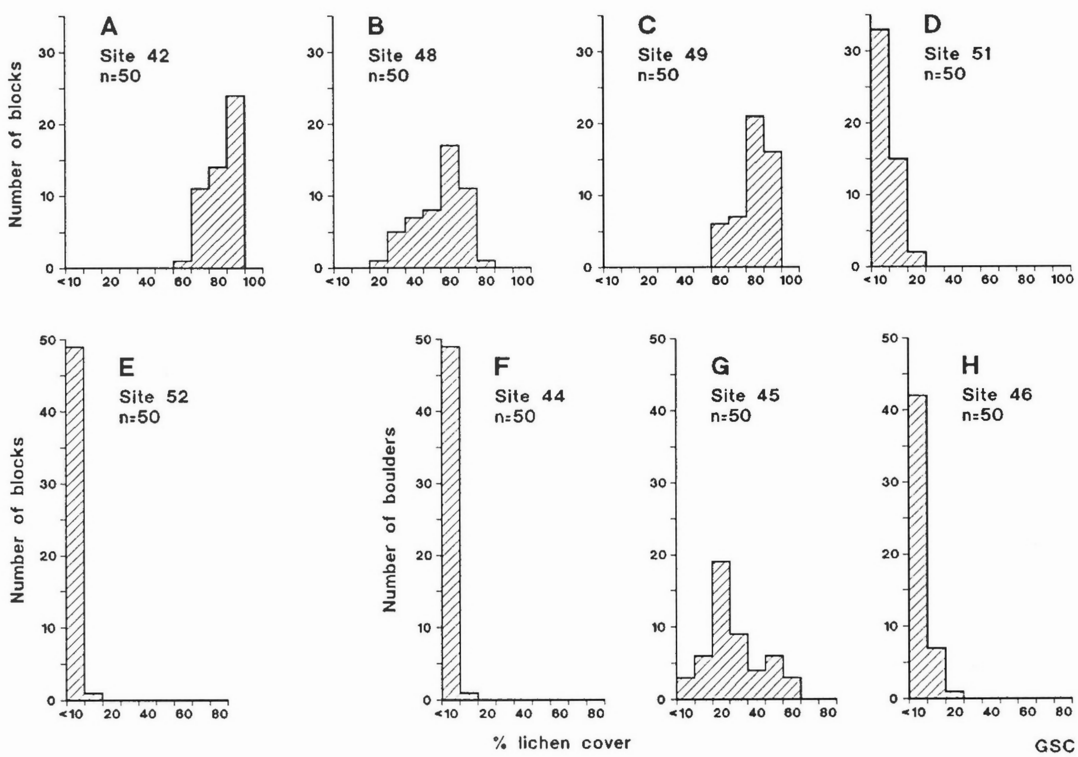


Figure 38. Histograms of per cent lichen cover on blocks at sites 42, 43, 48, 49, 51, 52, 44, 45, and 46.

Smaller glaciers also formed in this area during the Neoglacial but left only a subtle geomorphic record. The two north facing rock glaciers are separated by a 30 to 50 m wide strip of talus that is nearly lichen free, as are the adjacent side slopes of the two rock glaciers (Fig. 36). Upslope of the talus is striated bedrock. The striae point directly downslope and many talus blocks are similarly striated. The striae and nearly lichen free talus indicate that the low area between the two rock glaciers was occupied recently by a thin and weakly erosive glacier. A similar small glacier abutted the eastern

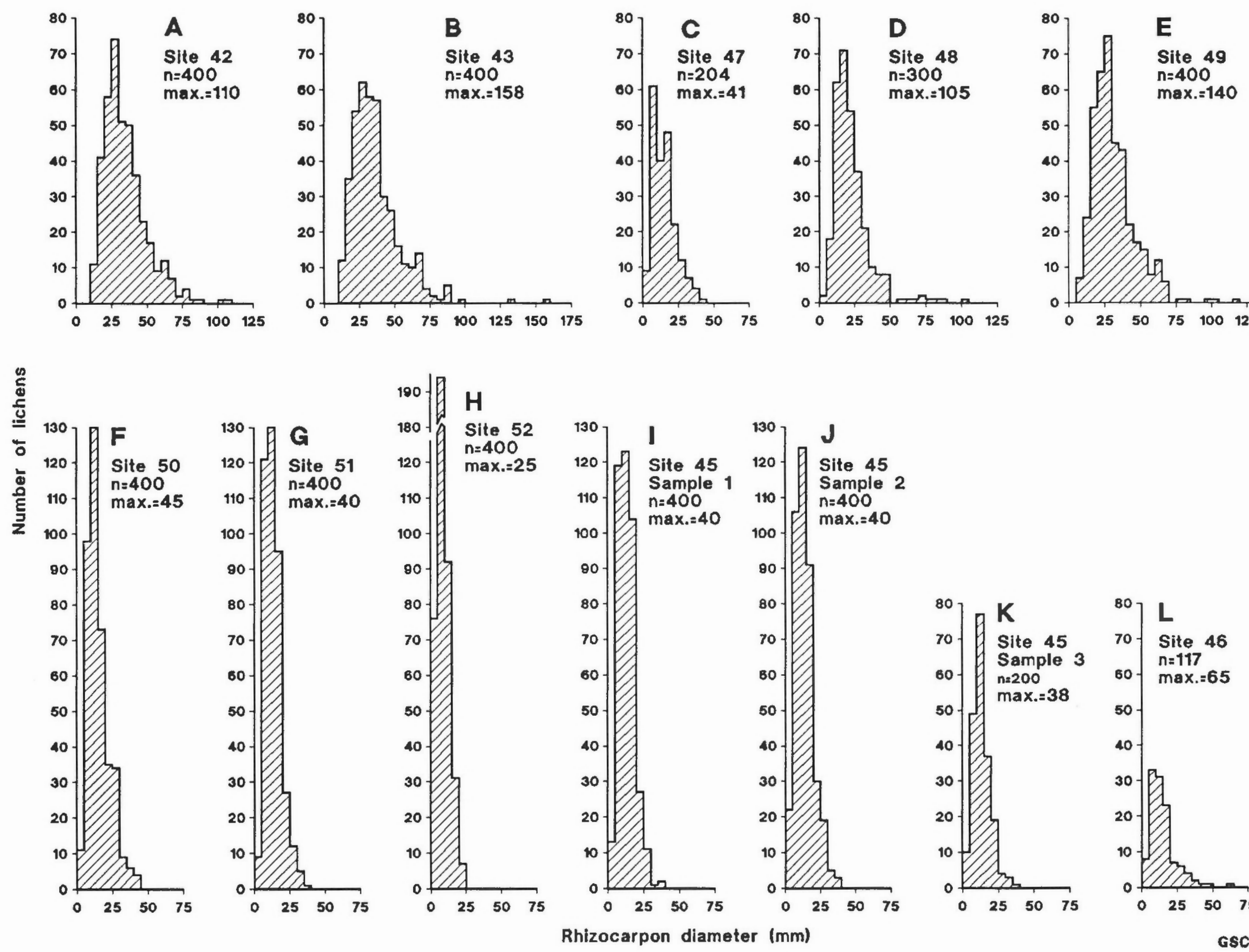


Figure 39. Histograms of *Rhizocarpon* diameters at sites 42, 43, 48, 49, 50, 51, 52, 45, and 46.

Figure 40. Up valley view of south facing rock glacier at sites 50,51, and 52. 204510-Q.

Figure 41. Neoglacial moraine ridge at site 44 with cirque glacier in background, August 4, 1983. 204510-R.

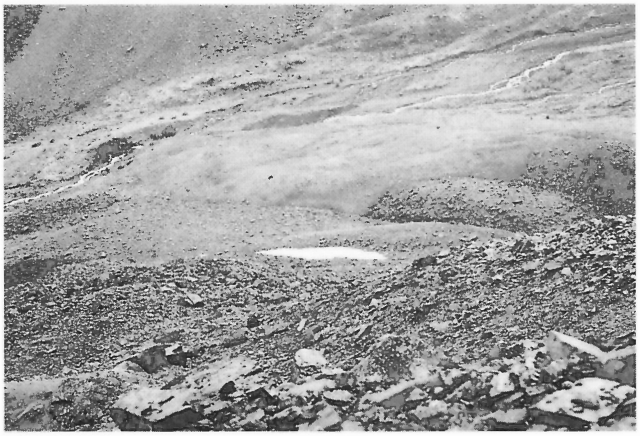


Figure 42. Cross-valley view of Neoglacial moraine at site 45. 204510-S.

flank of the more easterly north facing rock glacier and deposited a small lateral moraine (Fig. 35, site 46; Fig. 36). The moraine is sharp crested and contains some striated clasts. Clasts with both little or no lichen cover and with more mature lichen covers occur on the ridge. Most clasts have less than 10% lichen cover (Fig. 38H), similar to the moraine at site 44. But the size structure of the *Rhizocarpon* population more closely resembles that on the older moraine at site 45 (Fig. 39L, 39I-K).

Summary (areas 4 and 5)

Areas 4 and 5 contain rock glaciers with a variety of ages of substrates that are both older and younger than White River Ash. The substrate and *Rhizocarpon* community at site 49 (Fig. 43) are the youngest known to be definitely older than the ash. The rock glaciers appear to have a continuum of ages with little or no clustering of ages that might suggest causative climatic events. Even two adjacent, morphologically similar, north facing rock glaciers have different histories: one is of the same general age from head to toe (sites 42 and 43); the other progressively increases in age from head to toe (Fig. 43, sites 47, 48, 49), but even its oldest part is younger than the head of the adjacent rock glacier. The south facing rock glacier is unique among those examined; it has the youngest snout as well as a succession of still younger, higher lobes.

The two major Neoglacial moraines of area 5 are of widely different ages. A small glacier accumulated and built a moraine at a somewhat earlier time (Fig. 43, site 46).

Area 6

Area 6 comprises two alpine valleys connected by a col. Lichenometric studies were done on two rock glaciers and on Neoglacial moraines deposited by three glaciers (Fig. 44).

Rock glaciers

Two sites (53, 54) were studied on a large west facing rock glacier. The feature has well formed, arcuate, transverse ridges and furrows as well as large longitudinal ridges and furrows (Fig. 44) that originate at active talus cones. The frontal slope is steep, unstable, and nearly lichen free. The tread is completely mantled by phyllite blocks. The blocks are extensively covered in crustose lichens over most of the tread (Fig. 45A) but the uppermost transverse ridge has a less extensive cover (Fig. 45B). The *Rhizocarpon* population on the uppermost ridge is distinctly younger than that on the lower part of the tread (Fig. 46A).

The adjacent east facing rock glacier has a different morphology. It has strongly developed arcuate ridges that terminate headward at a steep ice contact escarpment. Nearly lichen-free Neoglacial till extends from the foot of the ice contact escarpment to an active glacier farther up valley (Fig. 47). This feature appears to be a "moraine glacier" (Johnson, 1973) that is, an ice cored glacial moraine complex that since deposition has flowed due to deformation of its ice core. A similar feature occurs in front of a west facing cirque glacier just south of site 54 (Fig. 44) and a few similar features have been recognized elsewhere in the region (Dyke, in press a-e). The rock glacier has unstable, lichen-free front and side slopes and is mantled completely by large phyllite blocks. It has a mature crustose lichen cover (Fig. 45C) and a *Rhizocarpon* population similar in size structure to that at site 53 (Fig. 46C,A).

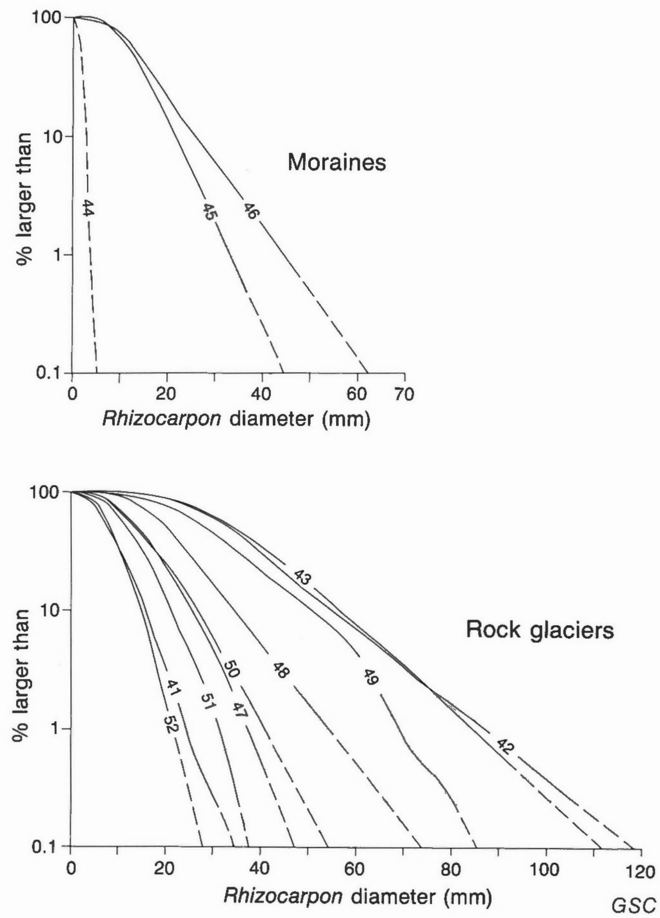


Figure 43. Cumulative curves of *Rhizocarpon* sizes on rock glaciers and Neoglacial moraines for sites in areas 4 and 5.

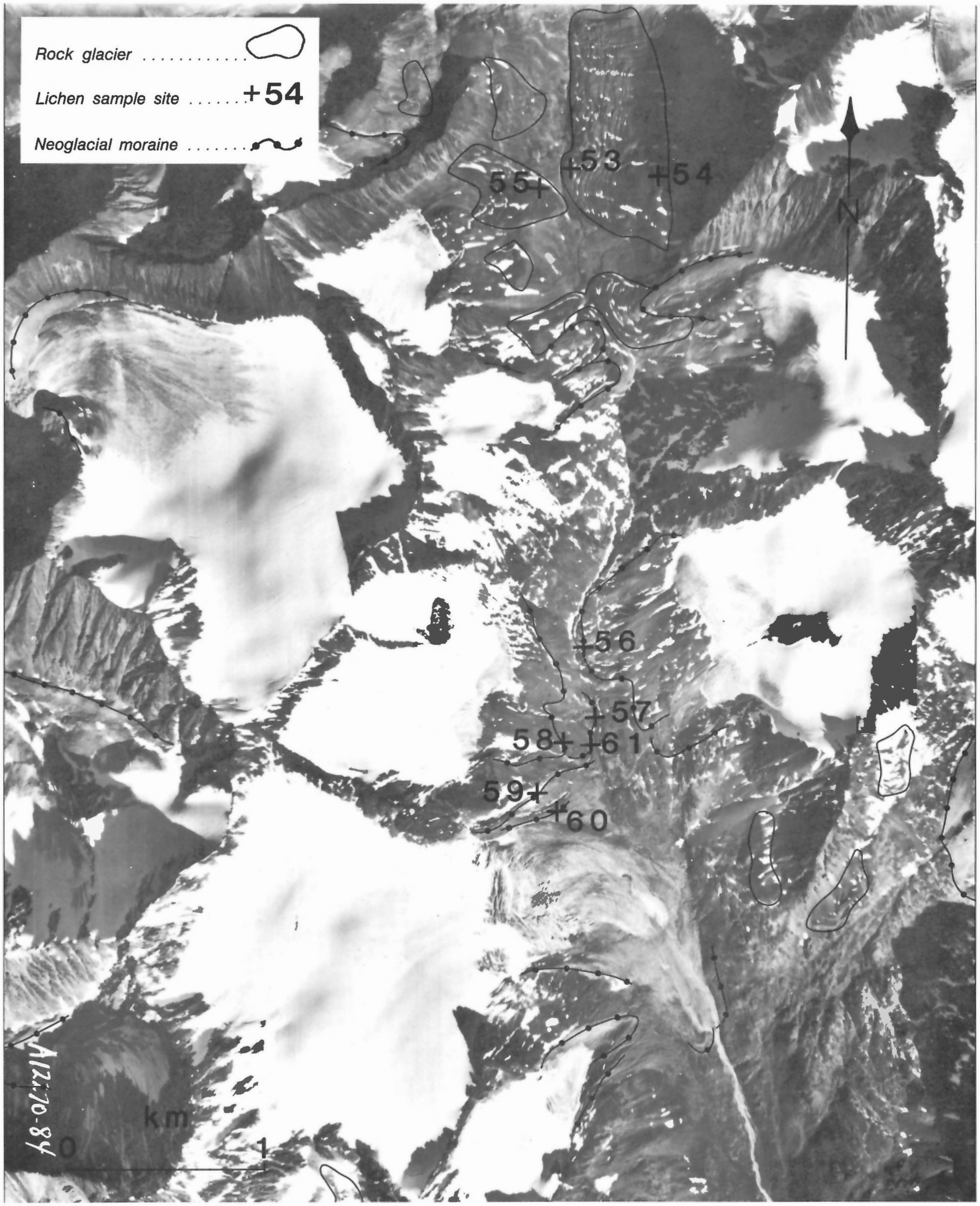


Figure 44. Sites studied in area 6. NAPL A12270-84.

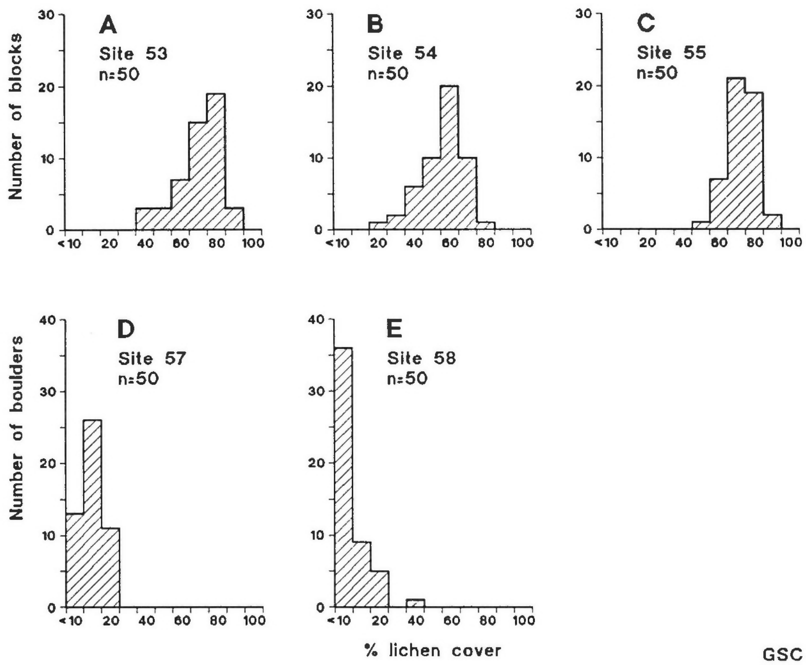


Figure 45. Histograms of percent lichen cover at sites 53, 54, 55, 57, and 58.

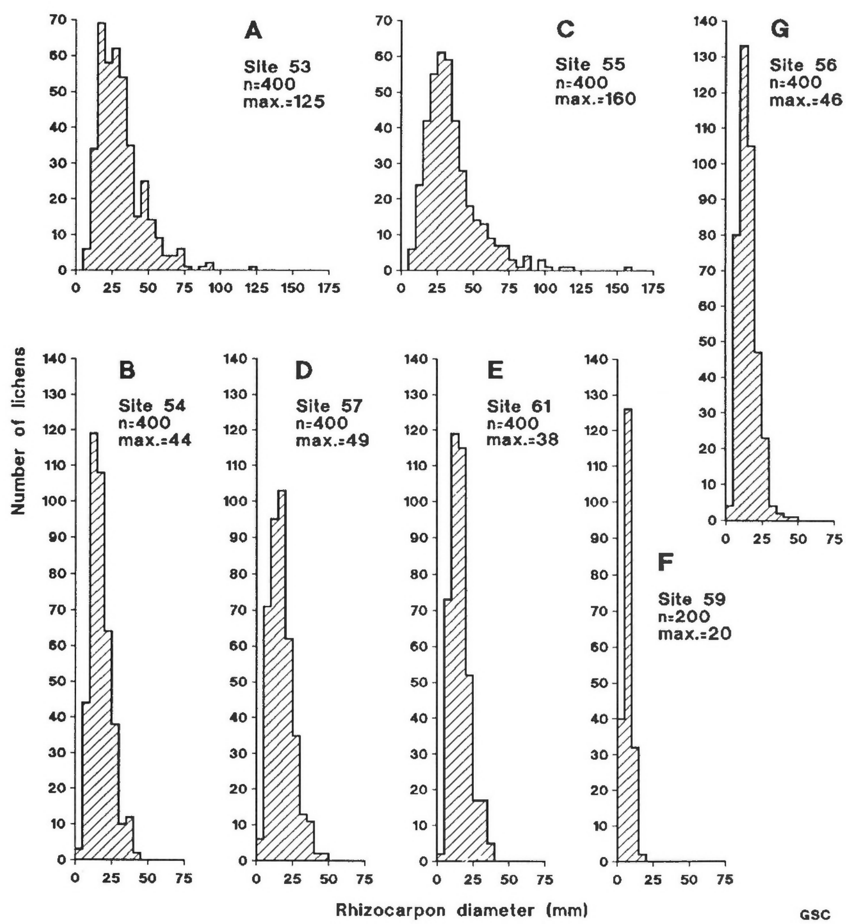


Figure 46. Histograms of *Rhizocarpon* diameters at sites 53, 54, 55, 57, and 61.

Figure 47. Cross-valley view of rock glacierized ice-cored moraine, the "moraine glacier" type of rock glacier, at site 55. 204510-T.

Neoglacial moraines

All glaciers of area 6 expanded during the Neoglacial and deposited one or two moraines. The oldest moraine examined (Fig. 44, sites 57 and 61) was deposited by an east facing glacier. It is about 2 m high and has a 60% boulder cover and a thin sod cover between boulders. Most boulders have a 10 to 20% lichen cover (Fig. 45D) and *Rhizocarpon* is rarely larger than 50 mm (Fig. 46D,E). The younger moraine formed by the same glacier (Fig. 44, site 58) is 10 m high and has a boulder and sod cover similar to the older moraine. Boulders on the younger moraine, however, have less lichen cover and *Rhizocarpon* is rare and does not exceed 22 mm diamter. The older of two lateral moraines deposited by another east facing glacier (Fig. 44, site 59) has more abundant *Rhizocarpon* which attains a maximum diameter of 20 mm (Fig. 46F). This moraine is steep sided and has an 80% cover of large monzonite blocks. The west facing glaciers deposited a single, 15 to 20 m high terminal moraine. *Rhizocarpon* diameters attain a maximum of 46 mm on this feature (Fig. 46G).

Summary

Rock glaciers of area 6 are mostly older than nearby Neoglacial moraines (Fig. 48) and older than White River Ash. At least one has a younger lobe on its upper tread that is roughly correlative with the older Neoglacial moraines. The rock glacier at site 55 is unique among those examined; it is a detached rubble-covered glacier snout that has continued to flow after detachment and indicates a period of glacial advance and deposition much earlier than is indicated by other Neoglacial moraines.

Other than the rock glacierized moraine at site 55, Neoglacial moraines of area 6 comprise three age groups. Substrates at sites 56, 57, and 61 are of approximately the same age (sites 57 and 61 are on the same moraine). The moraines at sites 58 and 59 are distinctly younger and a still younger moraine occurs at site 60.

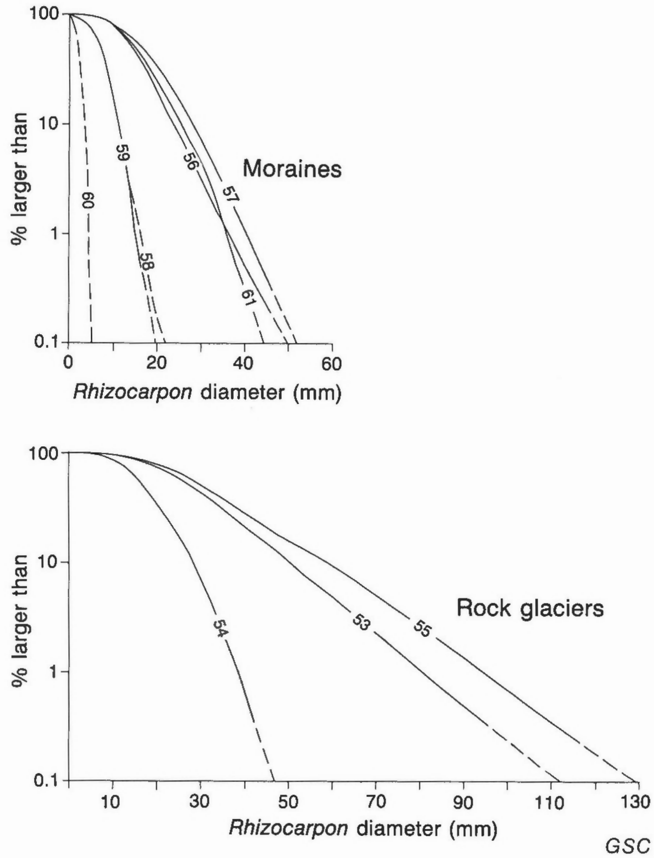


Figure 48. Cumulative curves of *Rhizocarpon* sizes on rock glaciers and Neoglacial moraines for sites in area 6.

Discussion of Rhizocarpon data

Regional correlations

The discussion of individual study areas demonstrates that different relative ages of substrate can be distinguished readily on the basis of the different size structures of the Rhizocarpon populations and more crudely on the simple basis of per cent lichen cover on boulders. This section addresses whether there are regionally correlative events within the Frances Lake map area and whether there are correlations between formation of rock glaciers, deposition of Neoglacial moraines, and expansion and retreat of former snowbanks.

The cumulative curves of *Rhizocarpon* sizes from all study sites (Fig. 49) show that rock glaciers occupy a much wider range of age than do Neoglacial moraines and lichen-kill sites. Within these ranges are features of many ages. The simplest and most tempting interpretation of these curves is that there is a continuum of ages of both rock glaciers and moraines below their respective maximum ages and that any gaps would likely be filled by sampling more features. Alternatively, apparent groupings represent time intervals when the processes of rock glacier formation and when glacial moraine construction were climatically induced.

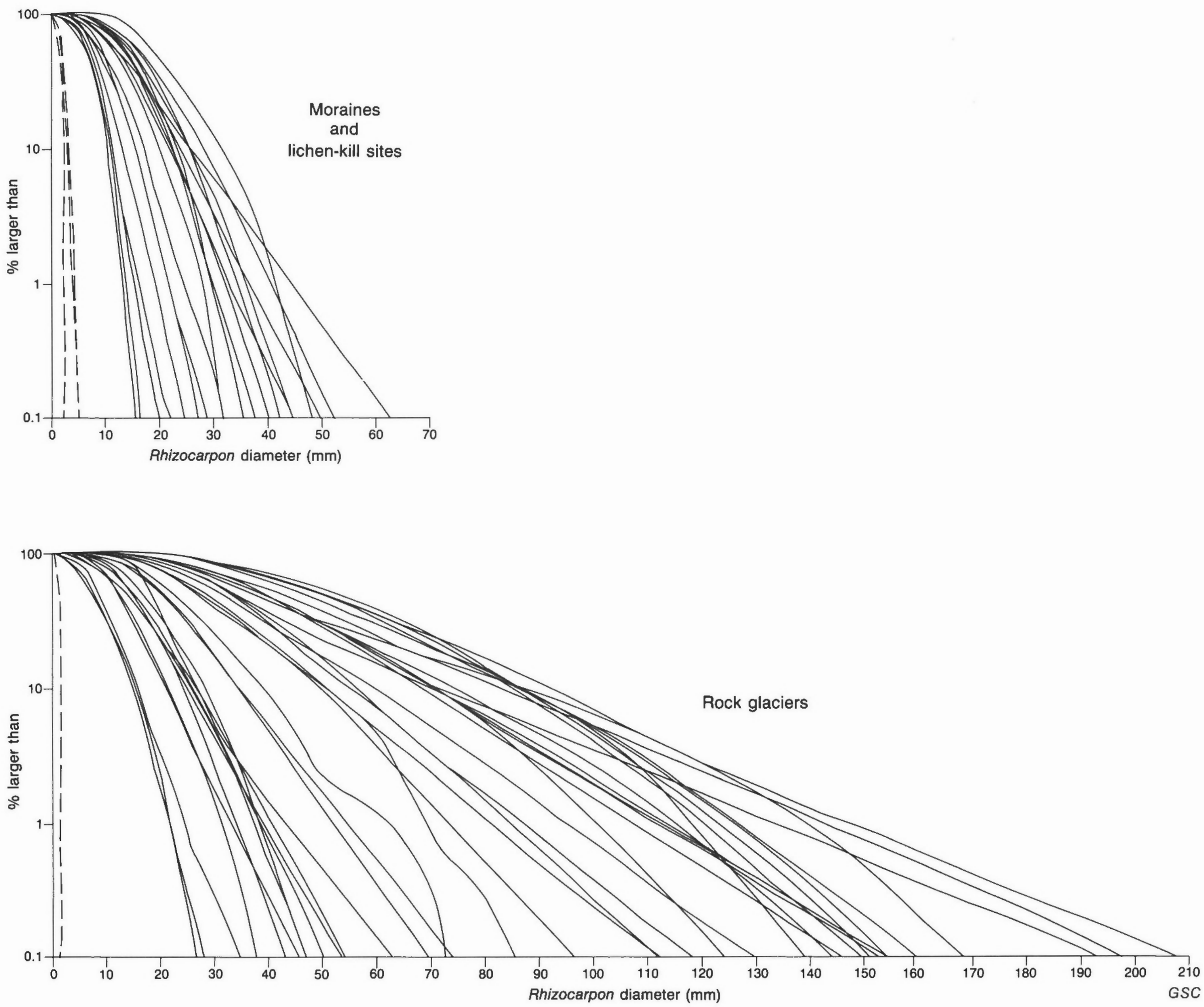


Figure 49. Cumulative curves of *Rhizocarpon* sizes on rock glaciers, Neoglacial moraines, and snowbank lichen-kill sites for sites in the Frances Lake map area.

moraines below their respective maximum ages and that any gaps would likely be filled by sampling more features. Alternatively, apparent groupings represent time intervals when the processes of rock glacier formation and when glacial moraine construction were climatically induced.

The best single statistic that corresponds to substrate age is one that approximates the size of the oldest indigenous (not redeposited) individual on the substrate. The most commonly used statistic in lichenometry is the size of the largest individual observed. But this approach incorporates the risk that the largest individual does not belong to the population that grew after substrate deposition. Such individuals can be easily recognized and excluded if the size structure of the population is analyzed. Here the oldest individual is defined as the "1 in a 100" lichen, whose size is the intercept of the cumulative curve and the first percentile. This statistic successfully differentiates substrates of different ages at all sites (Fig. 50A, 51A) and identifies possible age clusters of both rock glaciers (Fig. 50B) and moraines and lichen-kill sites (Fig. 51B). There is no convincing correlation between the ages of younger rock glacier features and Neoglacial moraines dating from the same general interval. Most rock glaciers are clearly much older than the Neoglacial moraines. Although the largest group of rock glaciers sampled is of the same general age as the moraines (Fig. 50B), all features of that age that were encountered were sampled, whereas only a small proportion of older features was sampled. Probably 90% of rock glaciers in the Frances Lake map area have first percentile *Rhizocarpon* sizes of 70 mm or more.

Approximate numeric ages

The youngest sampled substrate that is definitely older than White River Ash is at site 49 where the first percentile *Rhizocarpon* size is 72 mm. The substrate at site 3 has a sod cover which is devoid of White River Ash and has a first

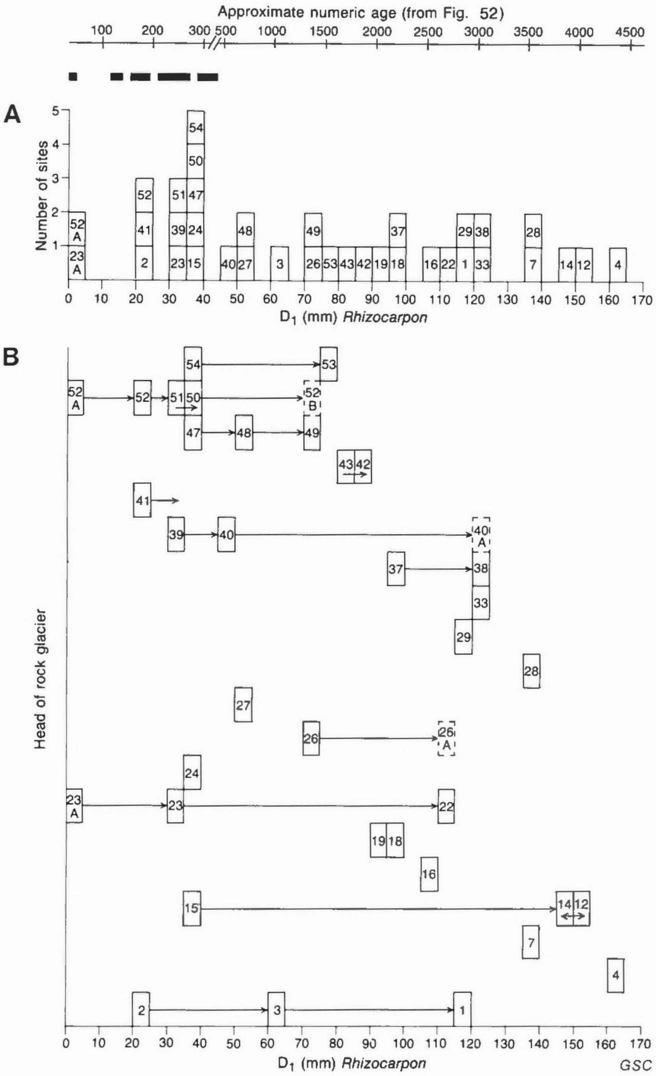


Figure 50. (A) First percentile (D_1) diameters of *Rhizocarpon* on morphostratigraphically related sites on rock glaciers and (B) histogram of first percentile diameters at the same sites. Numbers in boxes are site numbers; arrows indicate flow direction, substrates become older down flow. Boxes with dashed sides are estimates of Rhizocarpon sizes at sites where no measurements were made and these are omitted from the histogram shown in (B). The solid black bars above the histogram represent first percentile Rhizocarpon diameter on Neoglacial moraines.

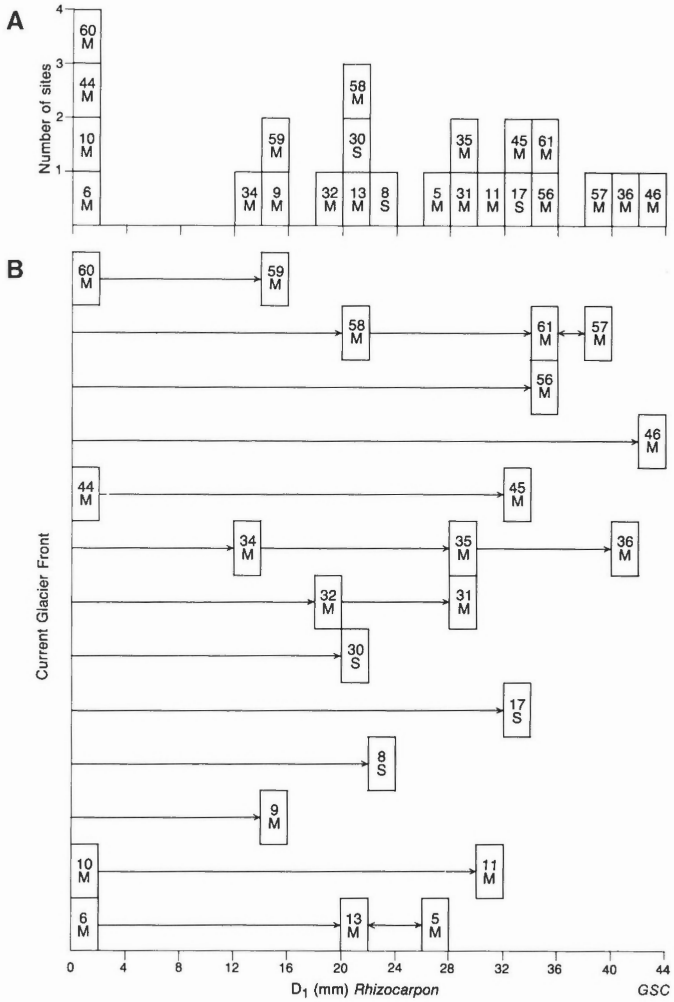


Figure 51. (A) First percentile (D_1) diameters of *Rhizocarpon* on morphostratigraphically related Neoglacial moraine sites, M, and snowbank sites, S, and (B) histogram of first percentile diameters at the same sites. Numbers in boxes are site numbers; arrows indicate increase in age down valley.

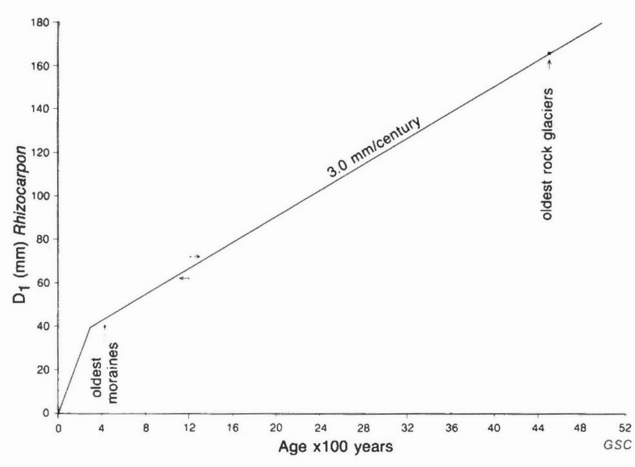


Figure 52. Tentative growth curve for *Rhizocarpon* in the Frances Lake map area based on the White River Ash datum, on a 3 century "great period", and a 3 mm/century linear growth rate thereafter.

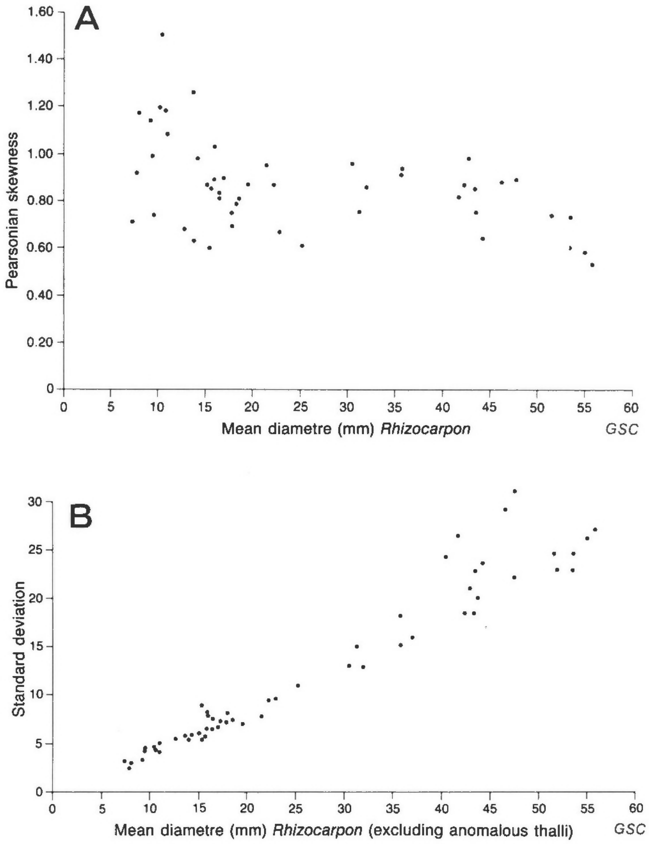


Figure 53. (A) Skewness versus mean diameter of *Rhizocarpon* populations and (B) standard deviation versus mean diameter of *Rhizocarpon* populations on substrates ranging from very recent (mean of 5 to 10 mm) to middle Holocene age (mean of 55 mm).

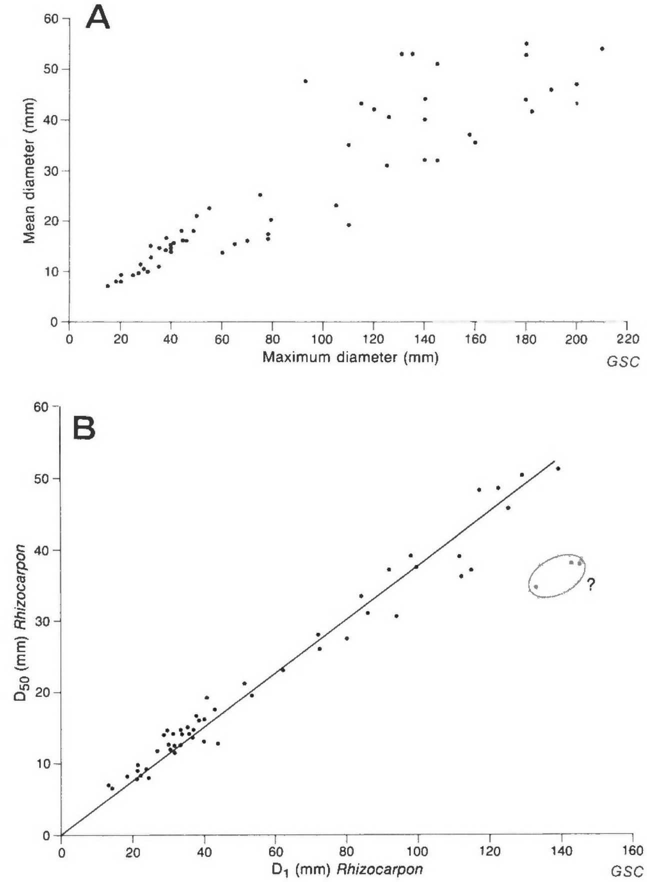


Figure 54. (A) Mean diameter versus diameter of the single largest individual in *Rhizocarpon* population and (B) median diameter (D_{50}) versus first percentile diameter (D_1) of *Rhizocarpon* population on substrates ranging in age from very recent to middle Holocene.

preliminary curve can be constructed based on two assumptions and on the single White River Ash datum (Fig. 52). Crustose lichens are thought to grow rapidly during the interval immediately after colonization and then to grow more slowly and at a linear rate (Locke et al., 1979). The initial period, so-called "great period", is thought to last 200 to 400 years when growth rates are of the order of 10 mm/century. Calculated growth rates during the subsequent linear phase from sites around the world, that in some ways resemble the alpine of southeast Yukon, range between 2 mm/century (West Greenland, Ten Brink, 1973) to 4 mm/century (Swedish Lapland, Denton and Karlén, 1973). Growth rates of 3 mm/century have been calculated for sites as far apart as the Colorado Front Range (Benedict, 1967), Cumberland Peninsula of Baffin Island (Miller and Andrews, 1972), and the St. Elias and Wrangle mountains of Alaska (Denton and Karlén, 1973). The preliminary curve of Figure 52, therefore, assumes a long term linear growth rate of 3 mm/century and a "great period" of three centuries.

On this admittedly tenuous basis, the oldest rock glaciers of the Frances Lake area are about 4500 years old. Rock glaciers continued to form throughout the middle and late Holocene and conditions for formation may have been enhanced around 3500 BP, 3000 BP, 2200 BP, 1400 BP, 700 BP, 250 BP, 200 BP, and less than 50 BP. It is possible, however, that a more complete sampling would eliminate this weak apparent climatic signal.

The oldest glacial moraine sampled continued to flow as a rock glacier after deposition and is much older than all other sampled moraines. The rock glacierized moraine has a first percentile *Rhizocarpon* size of 94 mm (site 55, Fig. 48) and hence an age of about 2300 BP. All other moraines are younger than about 400 years and hence fall within the last one-sixth of the interval of Neoglaciation as determined in the St. Elias Mountains of southwestern Yukon (Denton and Stuiver, 1966). Possible age groups occur at 400-300 BP, 250 BP, 200 BP, 150 BP, 100 BP, and less than 50 BP (Fig. 51B, 52).

These ages are too tentative to warrant correlation even with other sites in the northern Cordillera. They are presented only as the roughest estimates of the real ages but the differences in ages between groups of features should be approximately correct.

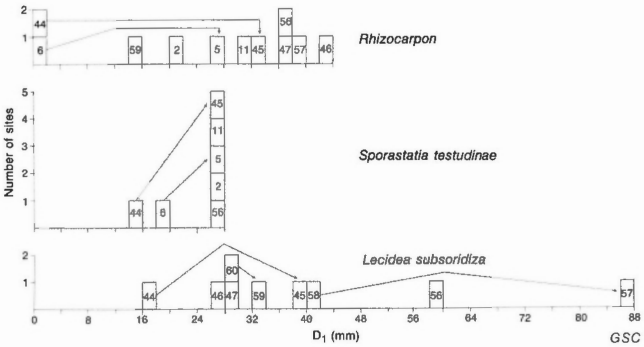


Figure 55. Histograms of first percentile diameter (D_1) of *Rhizocarpon, Sporastatia testudinea, and Lecidea* subsoridiza at selected sites. Numbers in boxes are site numbers. Arrows indicate specific morphostratigraphic relationships.

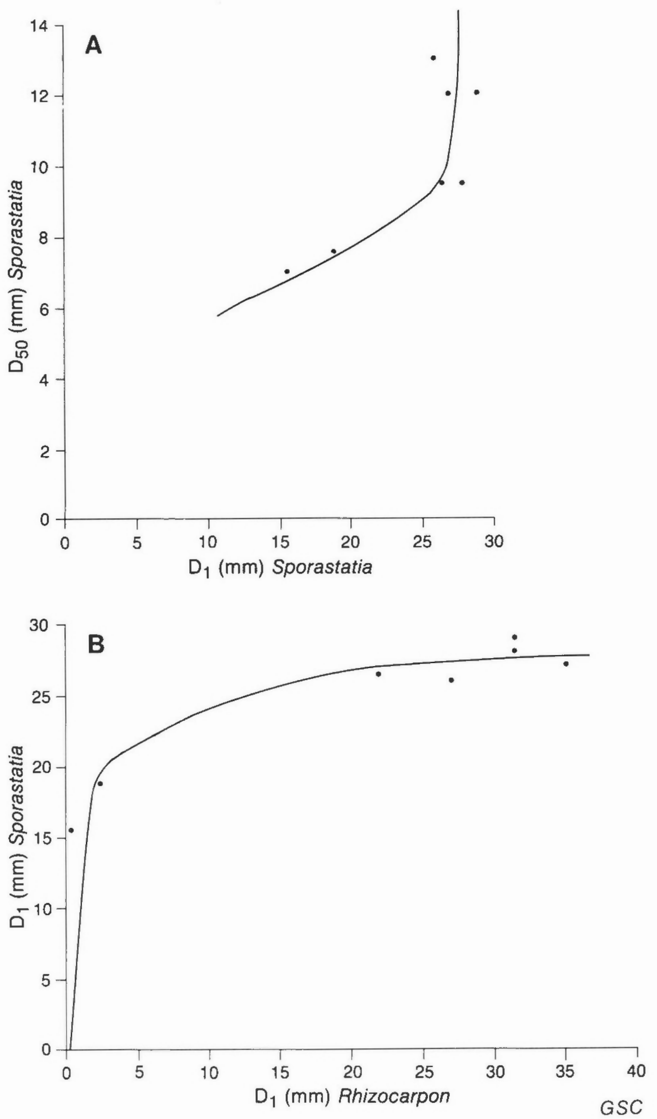


Figure 56. Median diameter (D_{50}) versus (A) first percentile diameter (D_1) of *Sporastatia testudinea* and (B) first percentile diameter of *Rhizocarpon* on selected younger substrates.

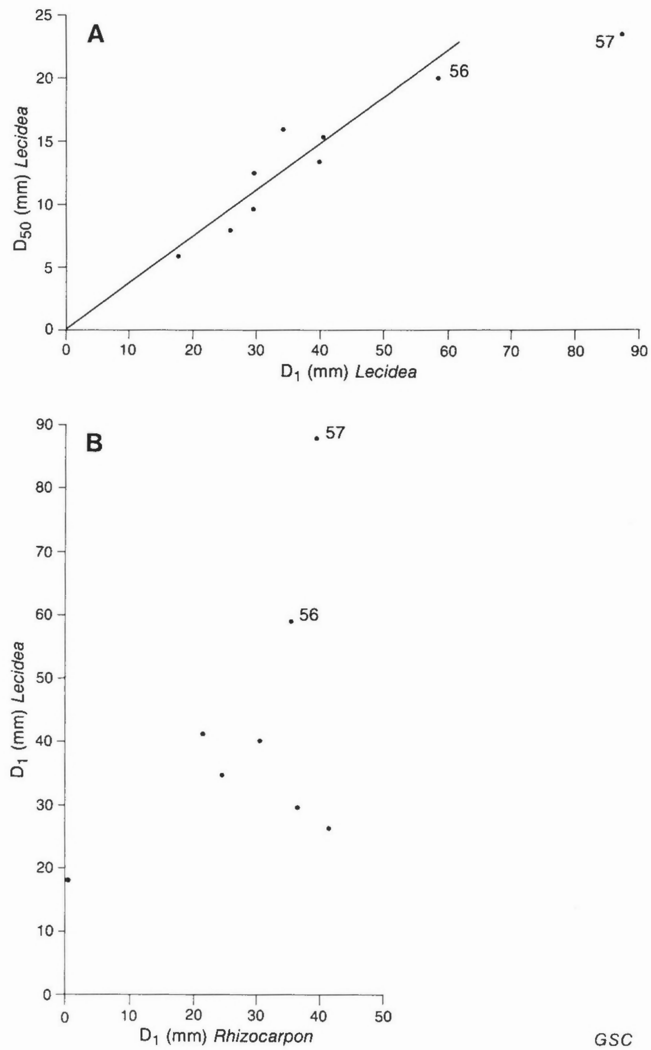


Figure 57. (A) Median diameter (D_{50}) versus first pecentile diameter (D_1) of *Lecides subsoridiza* and (B) first percentile diameter of *Lecidea subsoridiza* versus first percentile diameter of *Rhizocarpon* on selected younger substrates.

Effect of substrate age on lichen population

The *Rhizocarpon* data presented above represent the size structures of communities that range in age from about 50 years to about 4500 years. Hence we have the opportunity of examining how size structure changes as communities age by examining some obvious relationships between various population statistics.

All communities have positively skewed size structures. A plot of skewness versus the mean diameter, a function of age (Fig. 53A), indicates that skewness remains nearly constant with time, perhaps following an initial decline in skewness; for all ages of communities examined the mode lies on the small side of the mean and for even the oldest substrates there is no tendency toward establishment of a senescent population structure, wherein the mode would lie to the right of the mean. This implies that the lichenometric technique of *Rhizocarpon* size structure analysis should continue to differentiate substrate ages well beyond 4500 years.

The standard deviation also varies linearly with respect to the mean (Fig. 53B), which is to say, as the community ages, the range of ages of individual *Rhizocarpon* lichens in the community increases in constant proportion to the increase in the mean age. This implies that over the time span examined there is always sufficient unoccupied substrate for colonization and growth of younger lichens; a decrease or reversal in slope of the curve with time (with increasing mean size) would imply a tendency toward senescence. The increased scatter apparent for older communities could indicate that a larger sample (more than 400 measurements per site) is required to adequately assess the *Rhizocarpon* population size structure of older communities.

The mean size also varies approximately linearly with respect to the size of the largest single individual (Fig. 54A) but the scatter about the apparent linear trend becomes much larger with time. A plot of the first percentile size (D_1) versus the median size (D_{50}) (Fig. 54B) results in a remarkable decrease in scatter about the linear trend. This improvement arises from the exclusion of anomalously large individuals that predate substrate formation and it re-emphasizes the risk of using only the maximum lichen size as the proxy of age.

The linear relationship between D_1 and D_{50} means that as a community ages though a span of 4000 to 5000 years, the median size of individuals in the community remains proportionally constant to the size of the largest individuals. This could mean either of two things: Either all sizes of lichens grow (increase their diamters) at a constant rate or if growth rates changes through time due to a change in external (climatic) conditions, all individuals in a community adjust their growth rates by the same amount. In either case, under similar environmental conditions, the largest lichens grow at the same rate as smaller lichens. The important implication of this is that it supports the idea of a long linear growth phase for lichens following their brief initial "great period". The trend (Fig. 54B) shows no tendency to depart from the linear at the old end and this reinforces the conclusions stated above that middle Holocene communities have no symptoms of senescence and that the technique should continue to work in discriminating the ages of still older deposits.

SPORASTATIA AND *LECIDEA* DATA

While *Rhizocarpon* appears to be the only abundant lichen with circular thalli on deposits that have extensive lichen covers, younger deposits sustain abundant colonies of the silver grey species, *Lecidea subsoridiza*, and of the black species, *Sporastatia testudinea.* These species also occur abundantly on very young deposits that have not yet been colonized by *Rhizocarpon* or where *Rhizocarpon* occurs only as specks 1 to 2 mm across. *Lecidea* and *Sporastatia* were sampled, as were *Rhizocarpon,* on 13 younger deposits and data are presented and discussed here only summarily (Fig. 55).

Four observations are pertinent to this chronometric study: (1) All three data sets classify sites 44 and 6 as the youngest. (2) Where data were collected from nested sets of moraines, all three data sets assign correct relative ages (moraine 44 lies behind moraine 45 and moraine 6 lies behind moraine 5). (3) But not all apparent age relationships are consistent between data sets: the *Rhizocarpon* data indicate that site 46 is slightly older than site 57, whereas the *Lecidea* data indicate that site 57 is much older than site 46; and (4) *Sporastatia* achieves a consistent maximum size of 26 to 28 mm on deposits of site 2 age and older.

The last observation indicates that *Sporastatia* communities start to become senescent by the time *Rhizocarpon* has grown to a size of slightly more than 20 mm, that is, within 100 to 200 years. The same interpretation arises from a plot of D_1 versus D_{50} sizes of *Sporastatia* (Fig. 56A) which shows that increase in maximum size is arrested at about 25 mm while the median size continues to increase and approach the size of the maximum individual - all individuals in the community are approaching the size of the oldest, a senescent condition. A plot of maximum *Rhizocarpon* size (D_1) versus maximum *Sporastatia* size (Fig. 56B) illustrates the same point. *Sporastatia* explodes to 15 to 20 mm diameter before or while *Rhizocarpon* becomes established but grows little beyond 25 mm while *Rhizocarpon* rapidly attains and then exceeds this size. Clearly *Sporastatia* is of use in lichenometry only in subdividing substrate ages that are less than about 200 years old.

Over the range of age of substrates sampled (about 300 years) *Lecidea* appears to have a linear growth rate as indicated by a comparison of its maximum versus median sizes (Fig. 57A). The only data point that departs much from the linear trend is that for site 57. Since the relative age of site 57 based on the *Lecidea* data was misclassified with respect to the *Rhizocarpon* data, it is likely that errors were made in lichen identificaiton at site 57 and that some silver grey lichens other than *Lecidea* were measured. There is no indication of senescence occurring on substrates as old as site 56 so the species is probably useful in lichenometry for a period longer than the last 300 years. Initially *Lecidea* grows faster than *Rhizocarpon* but there is too much scatter in the small data set (Fig. 57B) to detect a long term trend in the relative growth rates.

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